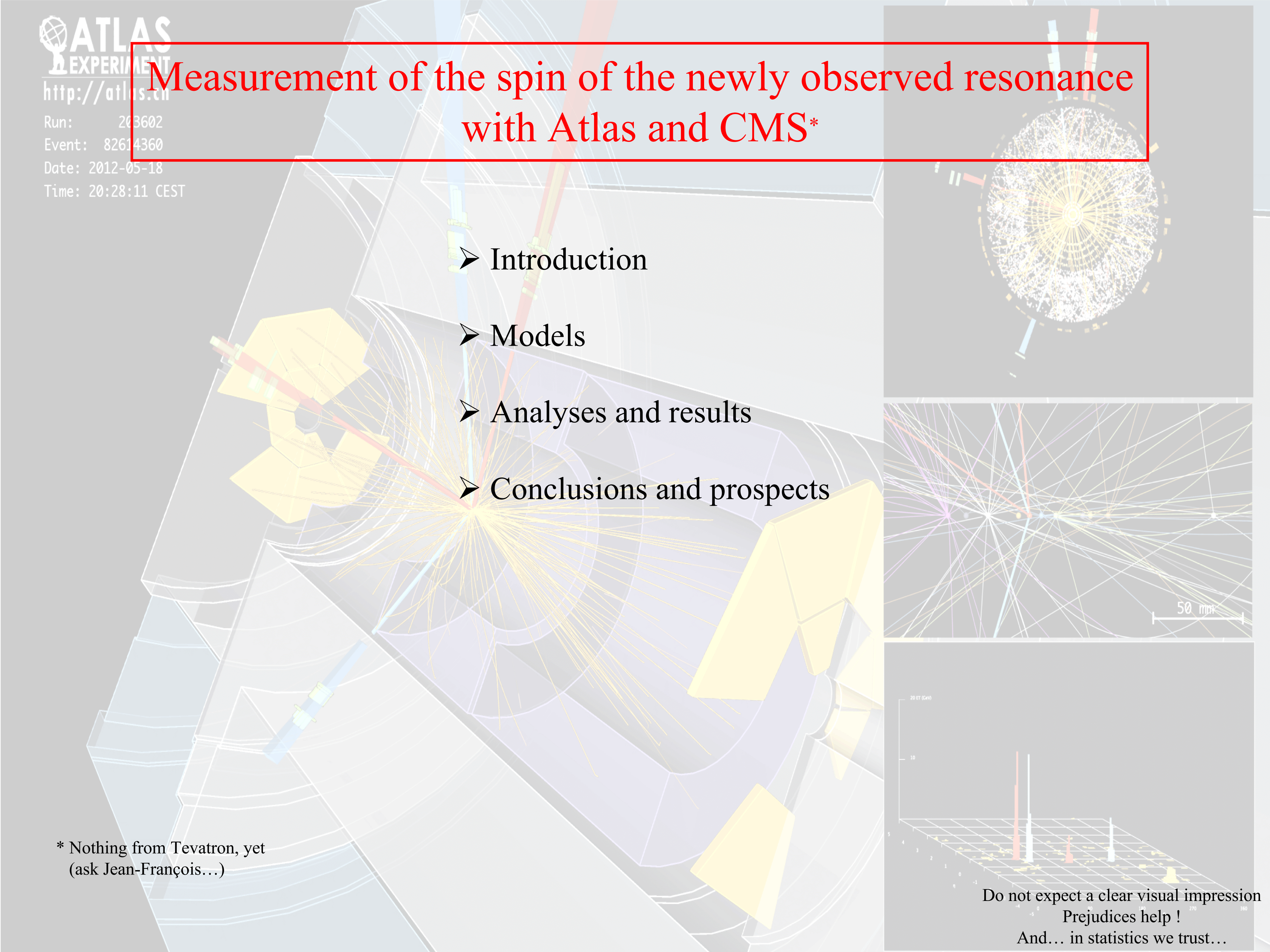
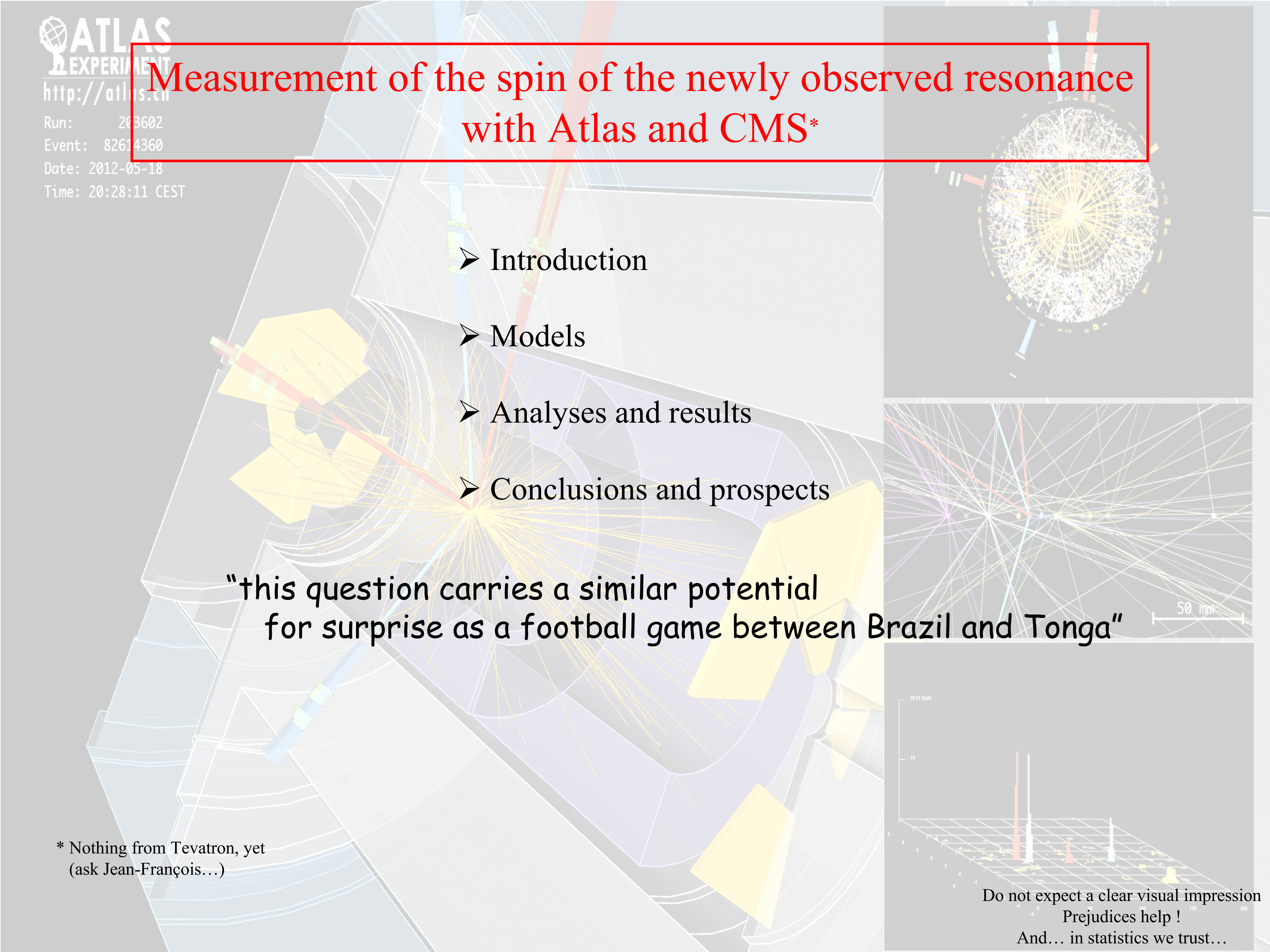
Measurement of the spin of the newly observed resonance with Atlas and CMS*



- Introduction
- Models
- Analyses and results
- Conclusions and prospects

* Nothing from Tevatron, yet
(ask Jean-François…)

Do not expect a clear visual impression
Prejudices help !
And… in statistics we trust…



Measurement of the spin of the newly observed resonance with Atlas and CMS*

- Introduction
- Models
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- Conclusions and prospects

"this question carries a similar potential
for surprise as a football game between Brazil and Tonga"

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Is this really the "SM Higgs" boson ?

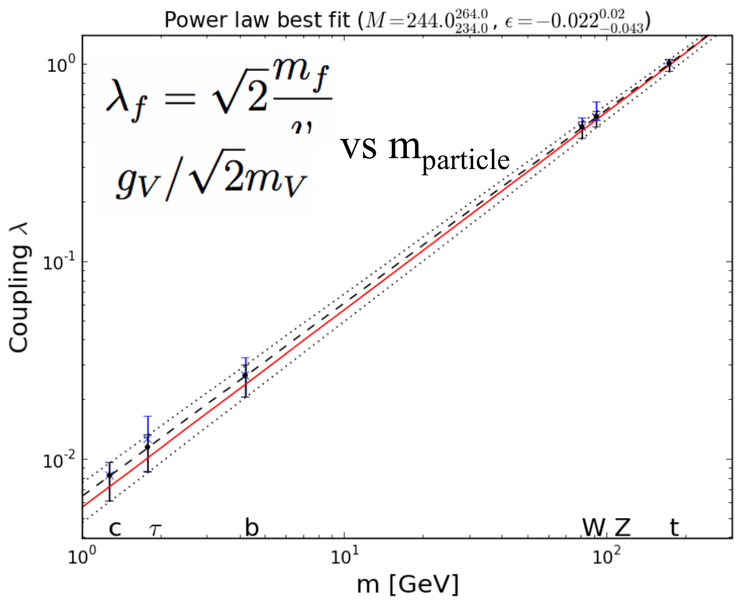
- Mass ~ 125 GeV/c^2 very much consistent with the preferred values from EW fits and theoretical prejudices

- Is it a neutral boson ? Yes : observation of e.g. $H \to \gamma\gamma$ ✓

- **Is it $J^{CP} = 0^{++}$? ($H \to \gamma\gamma \Rightarrow C = +$)**

- Does it couple to other SM particles ∝ mass ?

Ellis, You, 1207.1693
1303.3879



Coupling to V $= g_V = 2\frac{m_V^2}{v}$

Coupling to fermion = $\lambda_f = \sqrt{2}\frac{m_f}{v}$

Try that ansatz (SM : M = v, ε = 0)

$$\lambda'_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}$$

$$g'_V = 2\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}$$

Fit (M,ε) with available data
M = 244±15 GeV/c^2, ε = -0.022±0.030

Very consistent with SM…

Introduction

- The low mass region is not very favourable for J^P measurement
  many information in $H \to ZZ \to 4l$ but tiny yield
  relatively large yield in $H \to WW \to l\nu l\nu$ but final state not fully reconstructed (2 neutrinos)
  relatively large yield in $H \to \gamma\gamma$, but huge background

- Try to disentangle the SM Higgs boson from a singly produced spin J resonance
  - ✓ No look at spin higher than 2 for simplicity
  - ✓ Spin 1 forbidden(*) by the Landau/Yang theorem and the observation of $X \to \gamma\gamma$

    (For a massive particle of spin J, $J_z = M$ and momentum p, decaying to 2 photons
    the properly symmetrized 2-photon (helicity λ_1, λ_2) state is $|\Phi\rangle = |p,J,M,\lambda_1,\lambda_2\rangle + (-1)^J\, |p,J,M,\lambda_2,\lambda_1\rangle$
    with $|\lambda_1-\lambda_2| \leq J$. For $J = 1$, $\lambda_1 = \lambda_2$ and $|\Phi\rangle = 0$)
  - ✓ Associated productions (especially VBF) for the future

- The WW and ZZ observations already suggest $J^P = 0^+$ as being likely
  (exclude pure CP odd)

- The signal yield is a nuisance parameter,
  forget about the fact that μ is not so far away from the SM expectation…

One should keep in mind that if it's not something close to the SM Higgs boson,
it is a ***very smart impostor***

(*) can still try to exclude spin 1 (vector or pseudo-vector) with ZZ/WW alone, assuming at least two different particles produce the VV and $\gamma\gamma$ final states. Too exotic for me…

Models

Parameterising the most general $X_0 \rightarrow$ VV decay amplitude :

$$A(X \to VV) = v^{-1}\left(g_1^{(0)} m_V^2 \epsilon_1^* \epsilon_2^* + g_2^{(0)} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_3^{(0)} f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_\nu q^\alpha}{\Lambda^2} + g_4^{(0)} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

Λ = overall scale,
$f_{\mu\nu} = \varepsilon_\mu q_\nu - \varepsilon_\nu q_\mu$, $f_{\mu\nu}\sim = 1/2\ \varepsilon_{\mu\nu\alpha\beta} f^{\alpha\beta}$

$\Rightarrow$ 4 complex coupling constants

(in fact using only polarisation vectors, only three independent terms, see later)

$\Rightarrow$ For a 0^+ particle, $g_{1,2,3}$ (g_4) are parity conserving (violating)

For H_{SM}, @ tree level, $g_1 = 1$, $g_{2,3,4} = 0$. For a pure pseudo-scalar $g_4 = 1$, $g_{1,2,3} = 0$

From an effective Lagrangian point of view, g_1 ($g_{2,4}$ and g_3) would originate from a dimension 3 (5 and 7) operator

Parameterising the most general $X_2 \rightarrow VV$ decay amplitude :

$$A(X \to V_1 V_2) = \Lambda^{-1}\Big[2g_1^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + 2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta} + g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*(1)\mu\nu} f^{*(2)}_{\mu\alpha} + f^{*(2)\mu\nu} f^{*(1)}_{\mu\alpha} \right)$$
$$+ g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} f^{*(2)}_{\alpha\beta} + m_V^2 \left(2g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu} \right) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right)$$
$$+ g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + m_V^2 \left(g_9^{(2)} \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^4} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu} (q\epsilon_2^*) + \epsilon_2^{*\nu} (q\epsilon_1^*) \right) \right) \Big], \tag{18}$$

$\tilde{q} = q_1 - q_2$

$t_{\mu\nu} \sim X_2$ wave function

$\Rightarrow$ 10 complex coupling constants

(in fact using only polarisation vectors, only seven independent terms)

$\Rightarrow$ for the $gg \rightarrow X_2 \rightarrow \gamma\gamma$ channel : “only” 5 relevant

$\Rightarrow$ For a 2^+ particle, $g_{1\text{-}7}$ ($g_{8\text{-}10}$) are parity conserving (violating)

Parameterising the most general $X_2 \rightarrow q\bar{q}$ decay amplitude :

$$A(X_{J=2} \to q\bar{q}) = \frac{1}{\Lambda} t^{\mu\nu} \bar{u}_{q_1} \left(\gamma_\mu \tilde{q}_\nu \left(\rho_1^{(2)} + \rho_2^{(2)} \gamma_5 \right) + \frac{m_q \tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} \left(\rho_3^{(2)} + \rho_4^{(2)} \gamma_5 \right) \right) v_{q_2}$$

Too many degrees of freedom to study spin model-independently :
concentrate on the most simple, well motivated model

a spin 2 particle 2^+_m with minimal coupling, inspired from Gravitation :
→ replacing the Planck scale by the Electroweak scale
→ assigning a mass ~ 126 GeV to the graviton
(e.g. the first graviton KK excitation in Randall-Sundrum type models)

⇒ Keep only the term $\propto g_1/\Lambda$

For a "true" minimal model, ρ_1/Λ is fixed once g_1/Λ is (there is a single gravitational constant)
$\Rightarrow \sigma(\bar{q}q \to X_2)/\sigma(gg \to X_2) \sim 0.042$ (@ LO_{QCD} and using CTEQ6L1)

In Atlas, the fraction of events produced via $q\bar{q}$ annihilation has been scanned

This *minimal coupling* scenario is in fact already excluded at a high confidence level from the coupling analysis, since it predicts e.g.

✓ $\Gamma(gg) = 8\Gamma(\gamma\gamma)$ whereas HCP data $\Rightarrow \Gamma(gg) \sim (29\pm13)\,\Gamma(\gamma\gamma)$

✓ $\kappa_V \sim O(35)\,\kappa_\gamma$ whereas HCP data $\Rightarrow \kappa_V \sim (175\pm25)\,\kappa_\gamma$
(in RS type models)

The different benchmarks :

Type	couplings	channels	Experiment	comments
0^+_h	g_2	ZZ	CMS	
0^-	g_4	ZZ	Atlas/CMS	
2^+_m (almost-minimal)	g_1, g_5 ρ_1	ZZ/WW/$\gamma\gamma$	Atlas/CMS	Minimal coupling if $(qq \to X)/(gg \to X) \sim 4\%$
2^- (hybrid pseudo-tensor)	g_1 @ prod. g_8, g_9 @ decay	ZZ	Atlas	Strange ! Test analysis sensitivity to non minimal couplings
$1^\pm$		ZZ/WW	Atlas/CMS(ZZ)	(pseudo)vector

- The simulation of X production and decay is done with a LO generator (JHUgen)

- Do not care about the absolute signal yield prediction (*profiled away*)

  (however it plays an *important* role in the sensitivity !)

- Might care about the p_T spectrum of X, that could imply shape distortions w.r.t. LO production ($p_T = 0$)

  $\Rightarrow$ NLO (real) correction ? Not known but for SM Higgs boson

  Using accurate SM Higgs boson p_T prediction for the resonance p_T

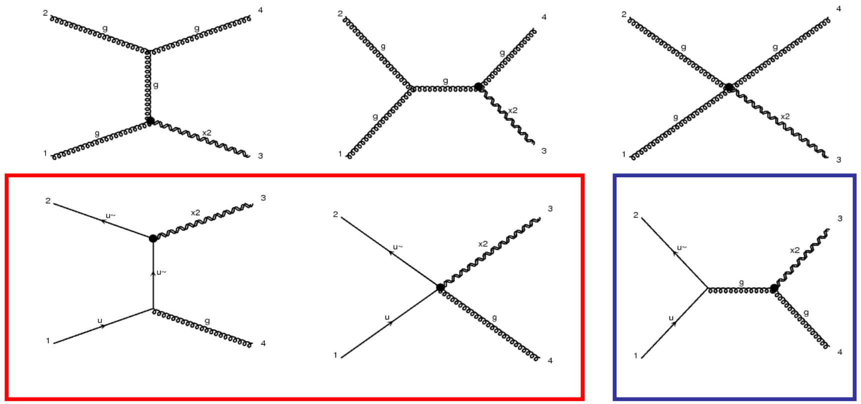
  (Only for gluon fusion; use p_T from parton shower for X produced in qq annihilation)

Side remark : the resonance transverse momentum

- Justifying the MC spin 2 reweighting to Powheg MC :
  assume the p_T generation comes mainly from ISR-type processes,
  With same argument could use N^{n}LO corrections to Drell-Yan to reweigh the spectrum from qq annihilation…

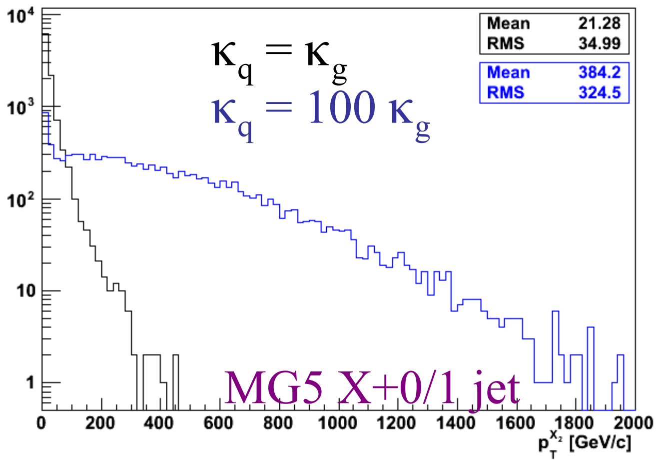
- In Atlas we scan the qq annihilation fraction (*i.e.* ρ_1 ($\sim \kappa_q$), g_1 ($\sim \kappa_g$) are independent parameters)
  In the minimal "tensor structure" scenario this leads to highly distorted p_T spectra from an absence of cancellation in the amplitude :

NLO real corrections



$\sim f_g(g_1,g_1,g_1)$

$\sim f_q(\rho_1,\rho_1,g_1)$



Need to think a little bit more about all these problematics…

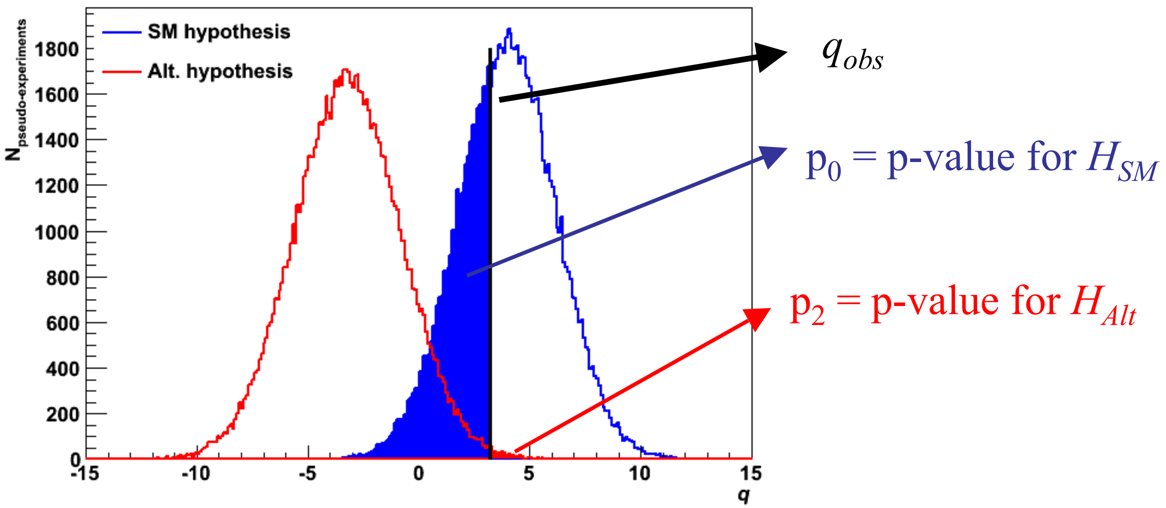
A word on statistical interpretation

- Always compare two hypotheses and determine the more likely given the data : use the (logarithm of the) Likelihood Ratio to rank the outcome of an experiment, typically

$$q = \ln \frac{\mathcal{L}(H_{SM})}{\mathcal{L}(H_{Alt})}$$

where H_{SM} is the SM hypothesis and H_{Alt} is the alternative (e.g. 2^+_m from gluon fusion)
(the likelihoods are in general simple products of Poisson probabilities over bins of discriminating variable distributions)

- Determine the q distribution under the two hypotheses (e.g. from toy experiments) and compute the probabilities (p-values)



To get the sensitivities, replace q_{obs} by the median of the distributions.

If X is indeed H_{SM}, the result of an ideal experiment with two sigma sensitivities would be

$p_0^{exp} = p_2^{exp} = p_2^{obs} = 4.55\%$

$p_0^{obs} = 50\%$

Any large deviation from 50% is a sign of a tension between the data and the tested hypothesis

The exclusion of the Alt. hypothesis in favour of the SM one is quantified by

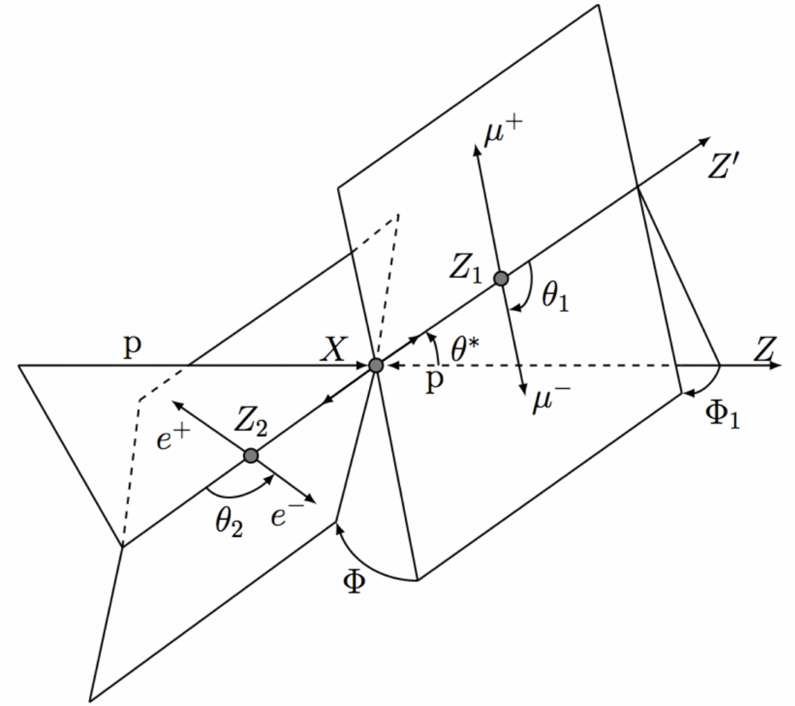
$CL_s(Alt) = p_2 / (1-p_0)$

Analyses and results

All analyses in Atlas (CMS) use a resonance mass of 125 (126) GeV/c^2, but very small impact (except for the combination…)

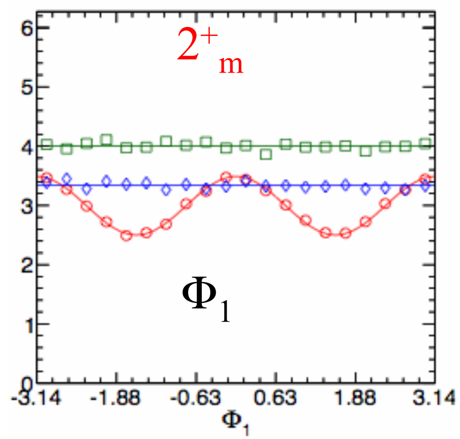
The golden four lepton channel (if only its yields were larger !)

4 body final state, fully reconstructed $\Rightarrow$ many clean variables to disentangle hypotheses
3 angles from the $Z^{(*)}$ decays (θ_1,θ_2,Φ), 2 angles for $Z^{(*)}$ production/dec. (θ^*, Φ_1), two masses

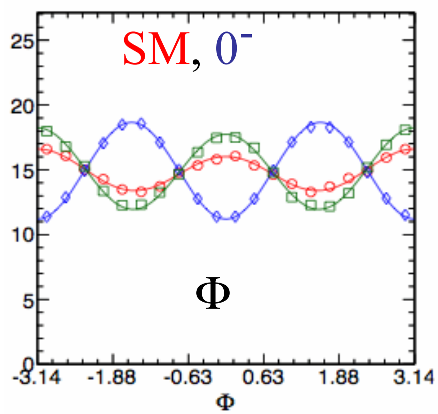


Not very sensitive to SM vs 2^+ yet
but powerful for parity

(Flat for SM)



(Almost flat for 2^+_m)



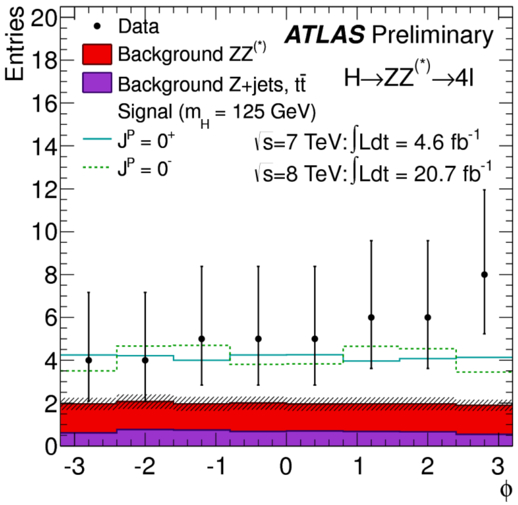
Both experiments combine the 7 (but not Φ_1 and θ* for SM vs 0^-) variables in a single discriminant :

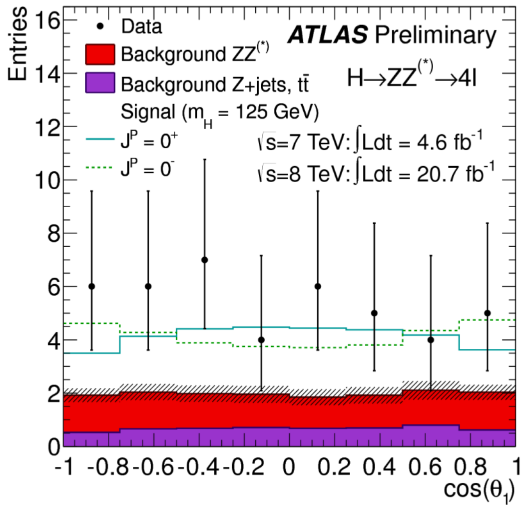
$$D_{J^P} = J^P\text{-MELA} = \frac{\mathcal{P}(H_{SM})}{\mathcal{P}(H_{SM}) + \mathcal{P}(H_{Alt})}$$

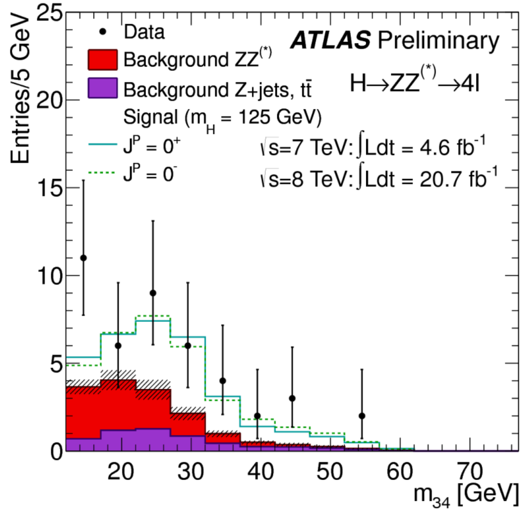
where P is the probability density function for (θ_1,θ_2,Φ, θ^*, Φ_1, m_{Z1}, m_{Z2}) for a given hypothesis corrected for acceptance and detector effects

Atlas has also independent analyses using BDT to combine the variables

Example for SM vs 0^- : the most relevant variables are Φ, $\cos\theta_1$ and m_{Z2}

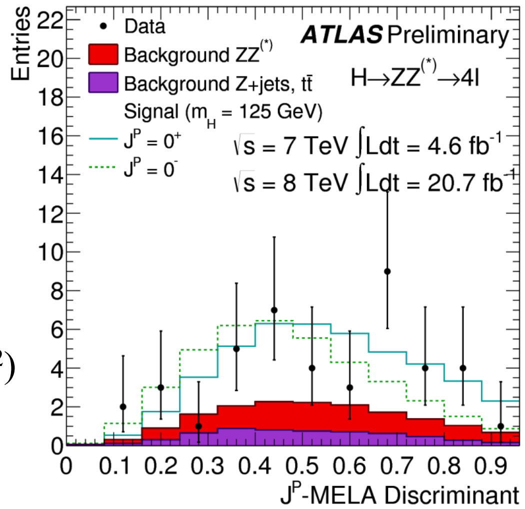




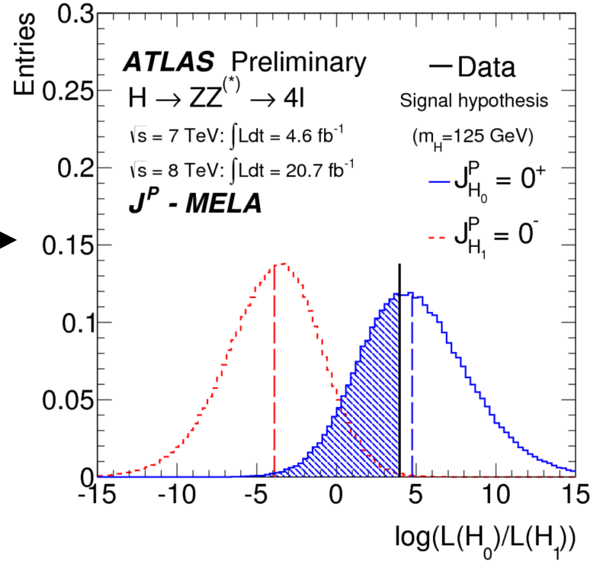


Final discriminant

(43 events with
$115 < m_{4l} < 130$ GeV/c^2)



q distributions

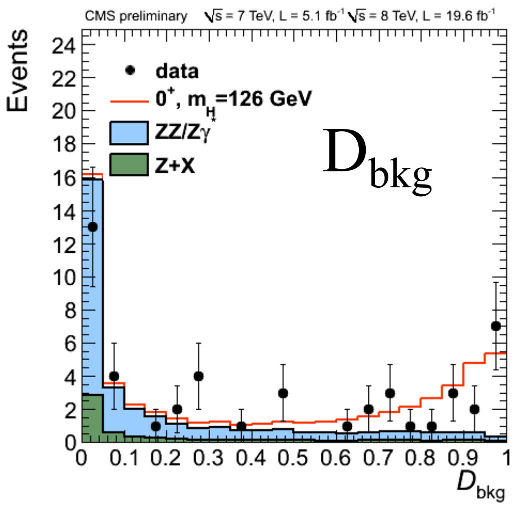


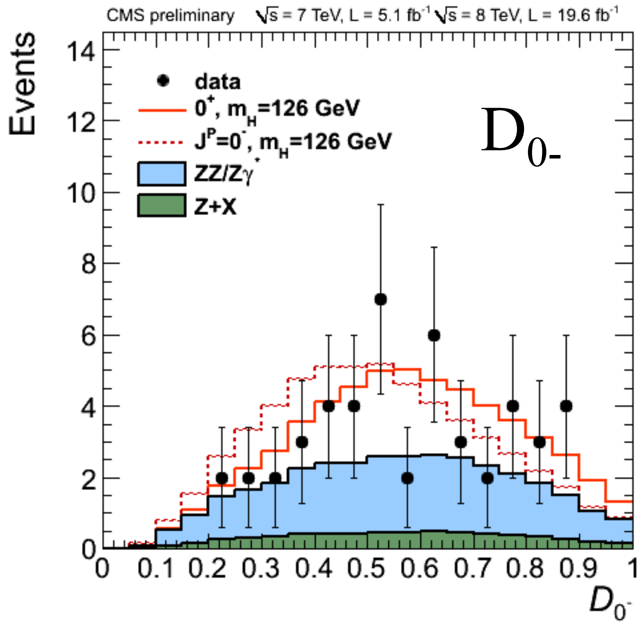
$p_{0-}^{exp} = 0.11\%$, $p_{0-}^{obs} = 0.22\%$, $p_{SM}^{obs} = 40.00\%$

$\Rightarrow$ $CL_s(0^-) = 0.4\%$ (2.2% for BDT analysis)

CMS uses a 2D analysis : D_{bkg} to separate signal and background and D_{JP} for the J^P discrimination

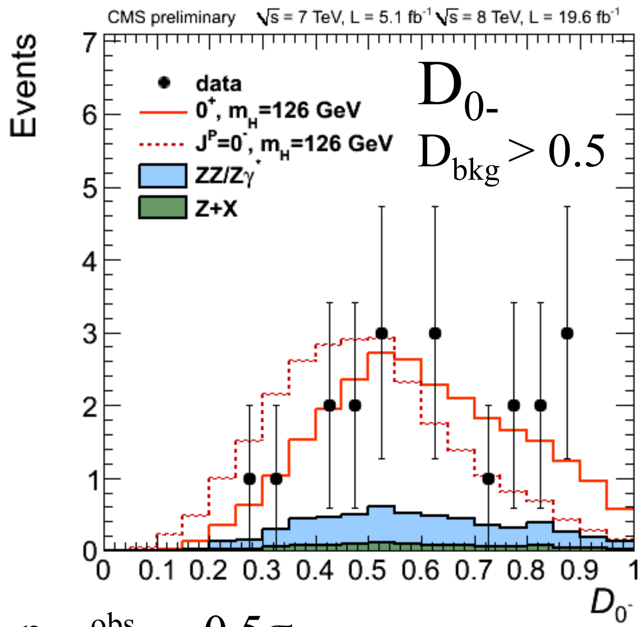
(48 events with
$106 < m_{4l} < 141$ GeV/c^2)





Selecting a signal-like region →

(the fit uses the full
2D (D_{bkg} , D_{JP}) plane)



$p_{0-}^{exp} = 2.6\sigma$, $p_{0-}^{obs} = 3.3\sigma$, $p_{SM}^{obs} = -0.5\sigma$

$\Rightarrow CL_s(0^-) = 0.16\%$

$\Rightarrow$ In both experiment the pure pseudo-scalar is disfavoured with CL higher than 99.6%
(97.8% CL for the BDT analysis in Atlas)

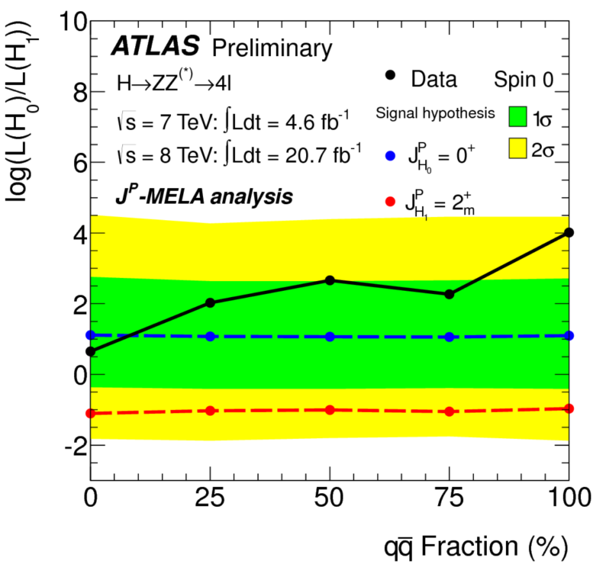
Results for the different benchmark cases :

J^P	p_2^{exp}	p_2^{obs}	p_0^{obs}	CL_s (%)
0^+_h	- / ~4.46	- / ~4.46	- / 50	- / 8.1
0^-	0.11 / 0.47	0.22 / 0.05	0.4 / 69.2	0.4 / 0.16
2^+_m, $gg \rightarrow X$ ($qq \rightarrow X$)	6.4 / 3.6 - / 4.46	11.0 / 0.35 - / 0.003	38.0 / 78.8 - / 96.4	18.2 / 1.5 - / < 0.1
2^-	0.32 / -	11.0 / -	8.0 / -	11.6 / -
1^-	0.10 / 0.26	2.70 / < 0.003	11.0 / 91.9	3.1 / < 0.1
1^+	0.31 / 1.07	0.28 / < 0.003	51.0 / 95.6	0.6 / < 0.1

ATLAS / CMS
(similar results for Atlas BDT analyses)

Atlas sensitivities profit from the fact that the measured yield is higher than the SM expectation $\hat{\mu} = 1.7^{+0.5}_{-0.4}$ @ $m_{\mathrm{H}} = 124.3\mathrm{GeV}/c^2$
It is the reverse situation for CMS $\hat{\mu} = 0.91^{+0.30}_{-0.24}$ @ $m_{\mathrm{H}} = 125.8\mathrm{GeV}/c^2$

For 2^+_m,
Atlas separation as a function of qq initial state fraction f_{qq} :
flat expectation : separation independent of the initial state



⇒ Against these models, the data favours the SM hypothesis

Starting to investigate mixed parity scalar state (CMS) : CP violation in the scalar sector

Rewrite the general amplitude with the 3 independent terms :

$$A(X \to V_1 V_2) = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left(a_1 g_{\mu\nu} m_X^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta \right)$$

$$= A_1 + A_2 + A_3$$

SM Higgs boson (tree) : $a_1 = 1$, $a_2 = a_3 = 0$, pure pseudo-scalar : $a_3 = 1$, $a_2 = a_1 = 0$

Investigate mixed state by measuring $f_{a3} = |A_3|^2 / (|A_1|^2 + |A_2|^2 + |A_3|^2)$

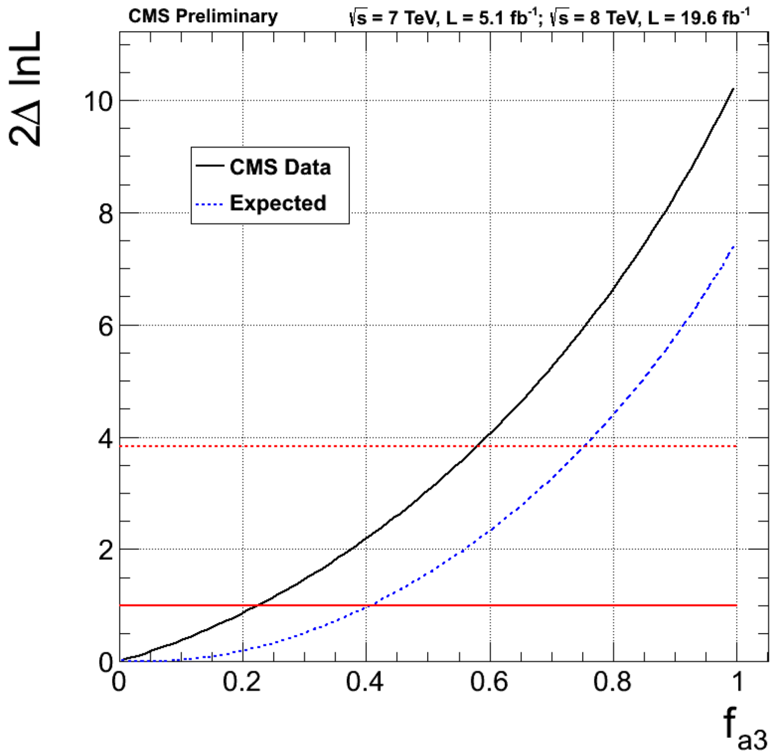
(a potential interference between A_1 and A_3 was found to have negligible impact on the yields or discriminating variable shapes)

f_{a3} is ***not*** the fraction of parity-even and parity-odd states, it is only a fraction in the decay amplitude

Use D_{0-} and neglect A_2 :

$\Rightarrow f_{a3} < 0.58$ @ 95% CL

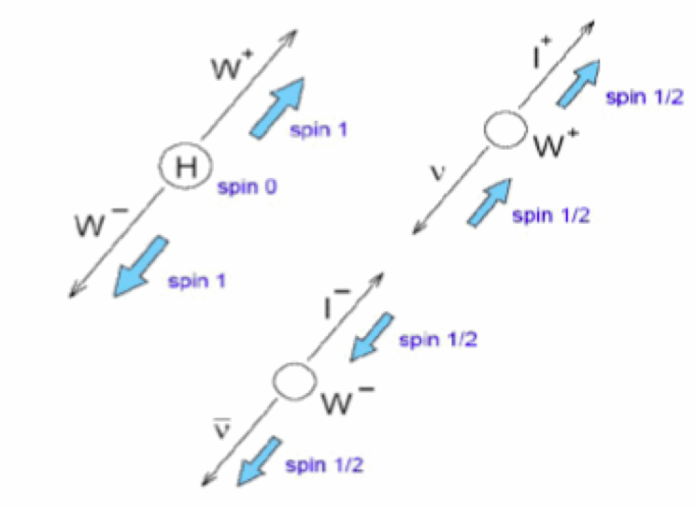
(0.75 expected)



A higher statistic but low S/B channel : $X \to WW$

Only for 2^+_m

In Atlas the scalar nature of the Higgs boson is used in the discovery analysis



Charged leptons close-by in space
→ small azimuthal separation $\Delta\phi_{ll}$
→ small di-lepton mass m_{ll}

⇒ Change analysis strategy to exploit this kind of variables without selection bias

Atlas uses only $X \to e\nu\mu\nu$ + 0 jet channel
other channels (SF leptons, + jets) bring to many background events with the looser cuts needed to stay as model independent as possible)

CMS uses $X \to e\nu\mu\nu$ + 0/1 jet channels (no shape analysis for the SF final states)

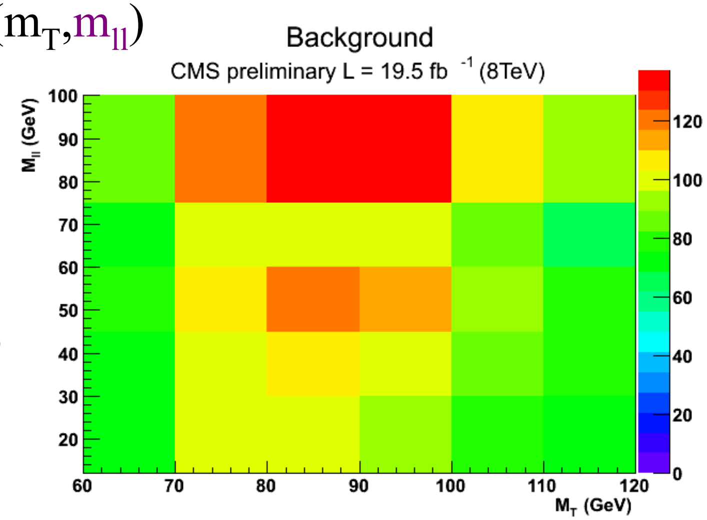
In both experiments, the m_T variable is used to discriminate signal and background and some other variables are used to disentangle the different spin hypotheses.
The most powerful spin analysers are m_{ll} and $\Delta\phi_{ll}$

$$m_T = \sqrt{2 p_T^{\ell\ell} \not{E}_T (1 - \cos\Delta\phi_{\vec{\not{E}}_T \vec{\ell\ell}})}$$

CMS uses a fit to 2D templates (m_T,m_{ll})

Example in the 0-jet bin :

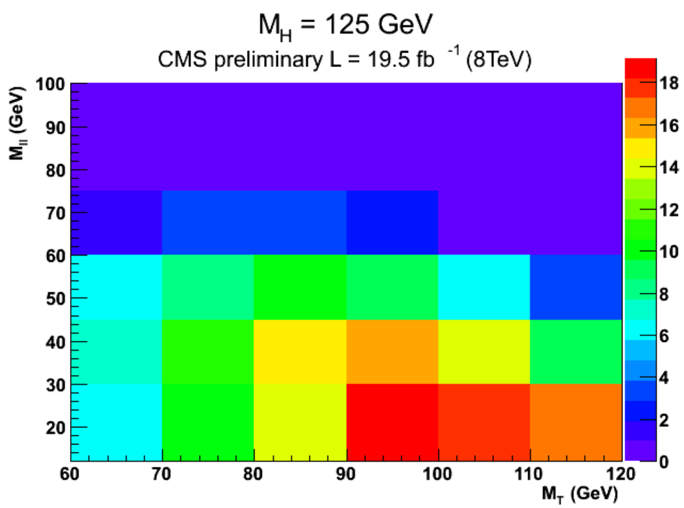
Background template
(same as the one used
for the discovery analysis)

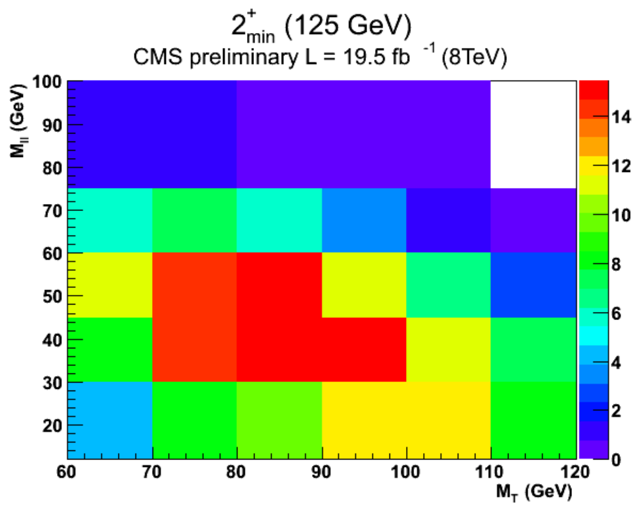


To be added to :

SM

2^+_m(gg)



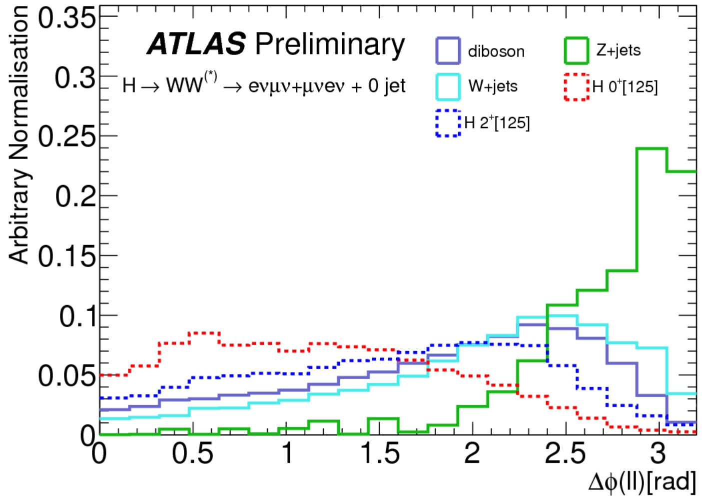


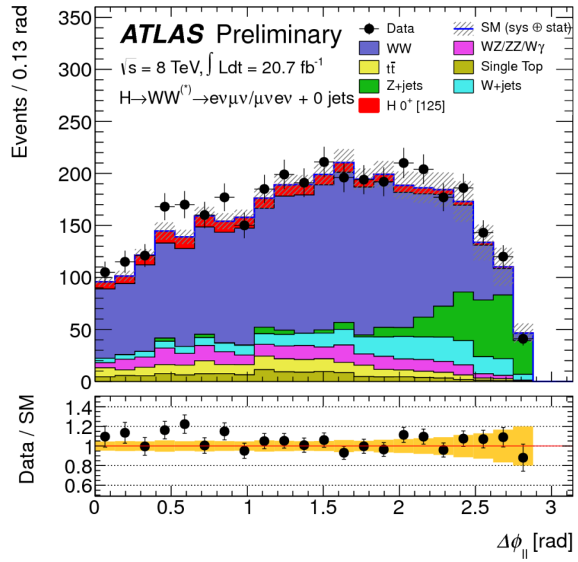
$\Rightarrow$ Adding the 0 and 1 jet bins :

CL_s = 14%, very slight preference for the SM

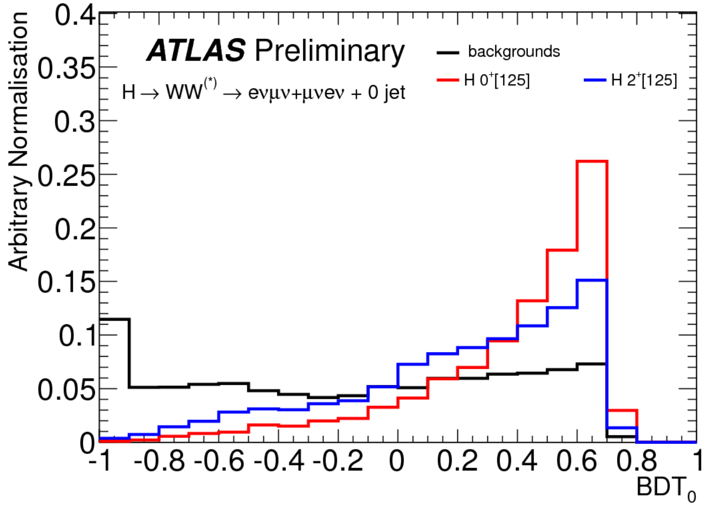
Atlas a bit more complicated… : also a 2D template fit (BDT_0, BDT_2)
where BDT_0 (BDT_2) combines 4 discriminating variables (m_{ll}, $\Delta\phi_{ll}$, $p_{T,ll}$, m_T) and is trained with SM (2^+_m) as signal

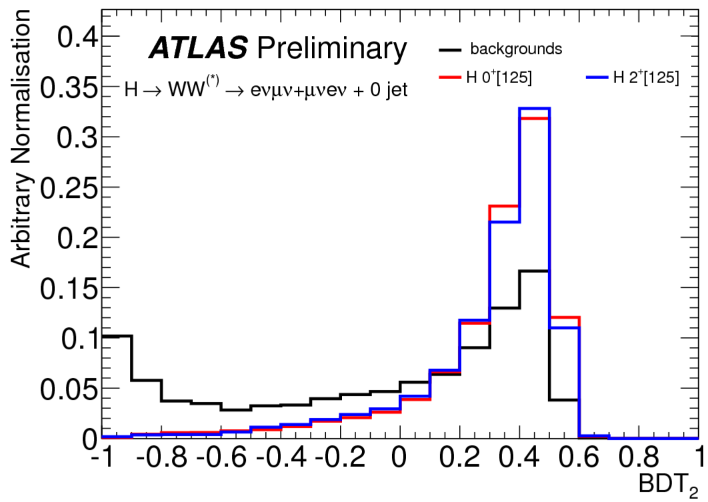
Example of input var. $\Delta\phi_{ll}$





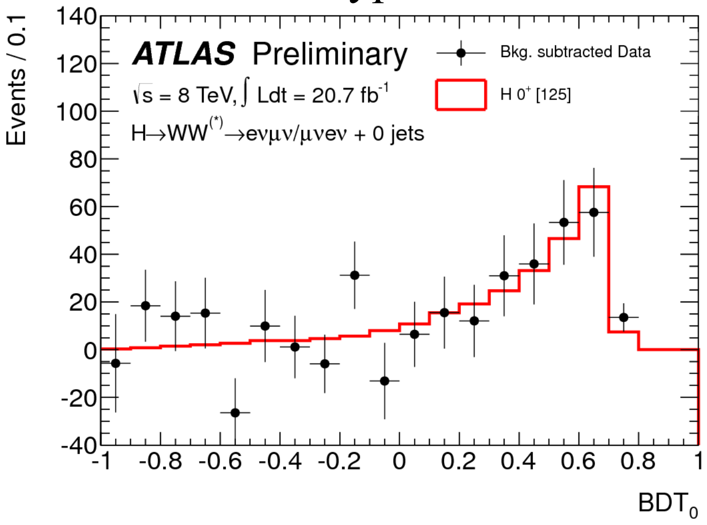
Shape of BDT outputs (f_{qq} = 25%) : BDT_0 more discriminating but BDT_2 still helps, especially at higher f_{qq} (retrained for each f_{qq})



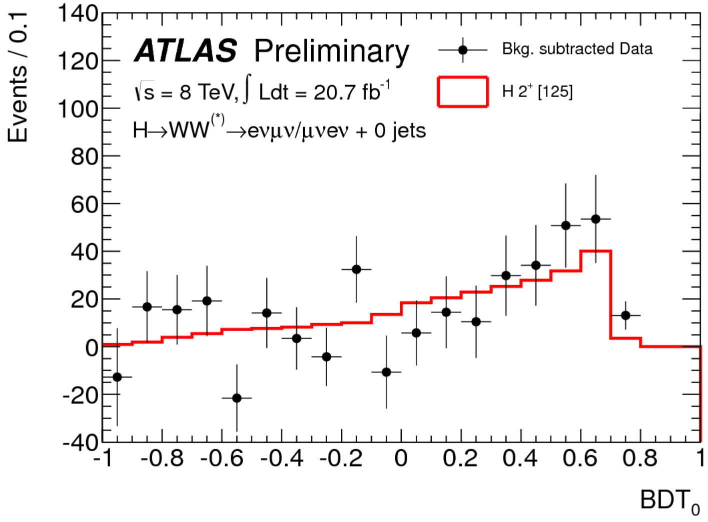


Fit results : projection of BDT_0 for background subtracted data

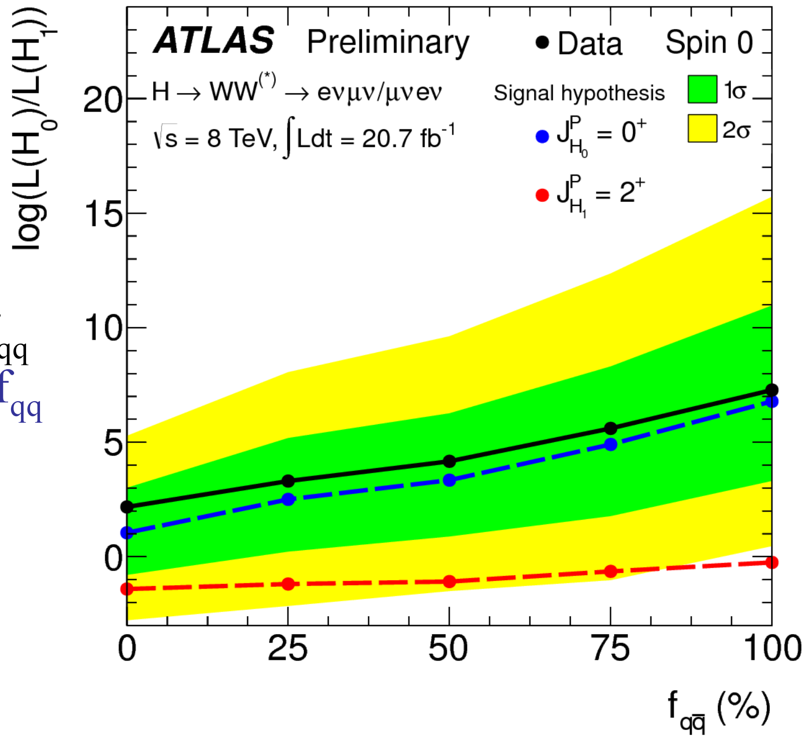
SM hypothesis



2^+_m (f_{qq} = 0.25) hypothesis



Separation vs f_{qq}
increases with f_{qq}



$\Rightarrow$ CL_s < 5% whatever f_{qq}

The fitted yield for the SM hypothesis is ~ 1.4 higher than in the discovery analysis, still OK (compatibility ~ 1.6σ)

What does H → γγ has to say ?

(Atlas only, 2012 data)

Despite large bkg and little information, might contribute where WW/ZZ are less sensitive
Relevant variable : photon production angle θ^*
whose distributions are easily obtained from the helicity formalism

$$\frac{dN}{d\cos\theta}(gg) \sim \Im_2\aleph_2 D_{22} + \Im_0\aleph_2 D_{02} + \Im_2\aleph_0 D_{20} + \Im_0\aleph_0 D_{00}$$

$$\frac{dN}{d\cos\theta}(q\bar{q}) \sim \Im_1\aleph_2 D_{12} + \Im_1\aleph_0 D_{10}$$

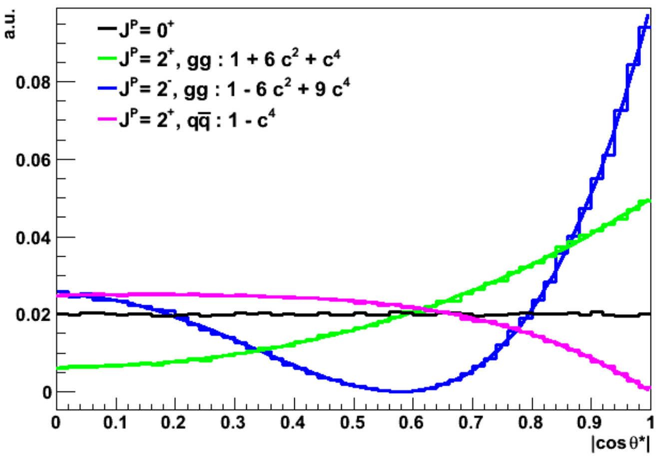
$\aleph$, $\Im$ are constants linked to the decay and production polarisation configuration
(a priori different for gg and qq)

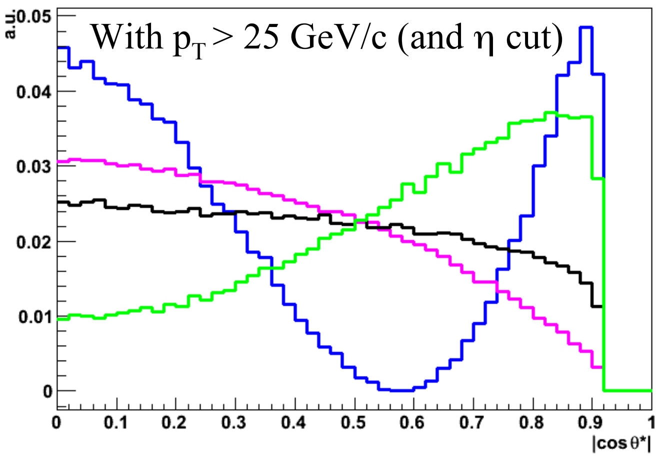
D_{ij} are sums of squared (little) Wigner matrices : $D_{ij} \sim \sum |d_{ij}^{J=2}(\theta)|^2$

In the minimal coupling scenario, $\aleph_0 = 0$ and $\Im_0 = 0$ (no coupling of X_2 to polarisation 0) $\Rightarrow$

$$dN/d\cos\theta^* \sim 1 + 6\cos^2\theta^* + \cos^4\theta^* \quad (gg)$$
$$\sim 1 - \cos^4\theta^* \quad (qq)$$

Example of expected distributions at $p_{T,H} = 0$:





For $p_{T,H} = 0$, $m_H = 125$ GeV/c², $p_{T,\gamma} > 25$ GeV/c
$\Rightarrow \cosh\Delta\eta < 11.5$
$\Rightarrow |\cos\theta^*| < 0.92$

➢ Standard $H \rightarrow \gamma\gamma$ selection except for the $p_{T,\gamma}$ cut :

from absolute ($p_T > 30/40$ GeV/c) to relative $p_T > 0.25/0.35\ m_{\gamma\gamma}$

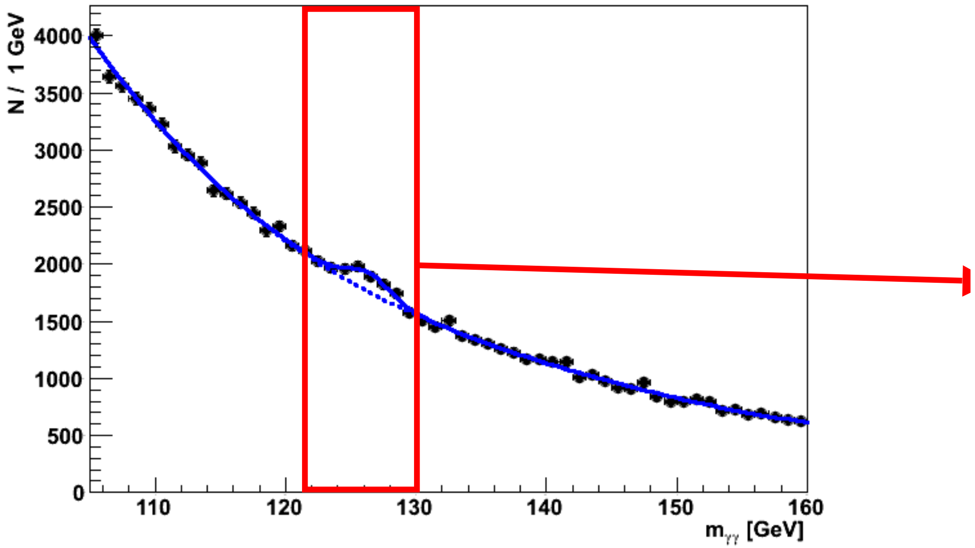
remove most of the correlations between $m_{\gamma\gamma}$ and $\cos\theta^*$ for the background allowing a better control of the shape

➢ The signal region (SR) is defined as $m_{\gamma\gamma} \in [122,130]$ GeV/c^2 :

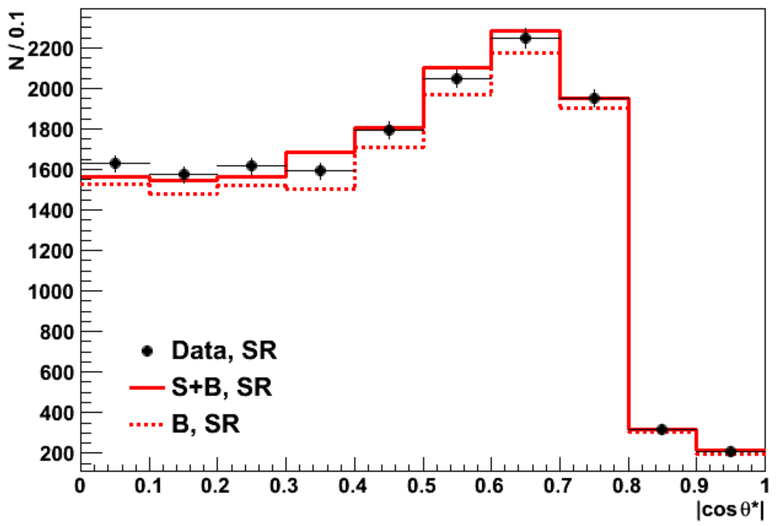
$\Rightarrow$ 94471 selected events, 14982 in SR, ~ 385 signal events from SM expectation

Main challenge : measure the $\cos\theta^*$ distribution of ~ 690 signal events (for $\mu \sim 1.8$) on top of ~ 15 K background events

$m_{\gamma\gamma}$: main handle for bkg rejection

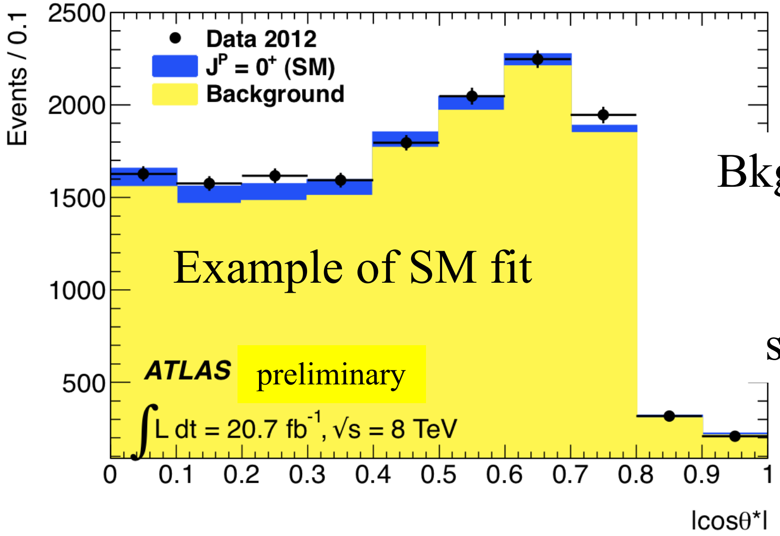


$\cos\theta^*$: main handle for spin measurement



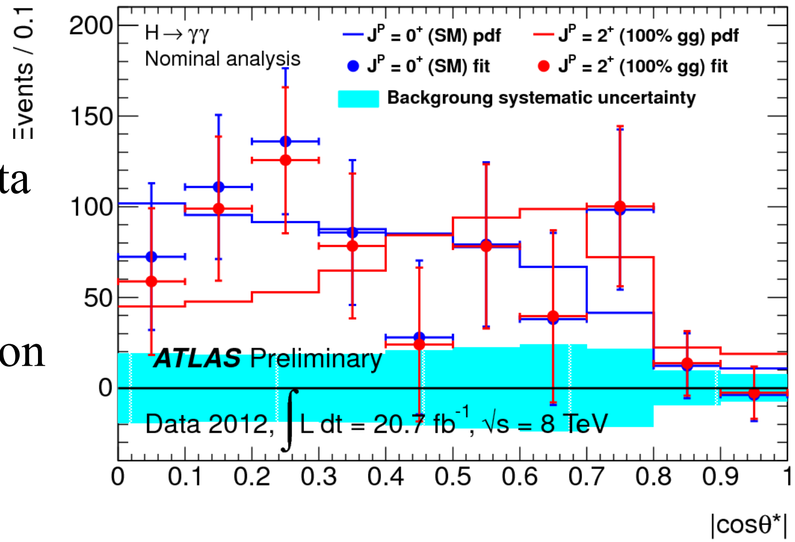
2^+_m with 100% gg fusion

Fit the data for the two hypotheses



Bkg subtracted data

compared to signal expectation



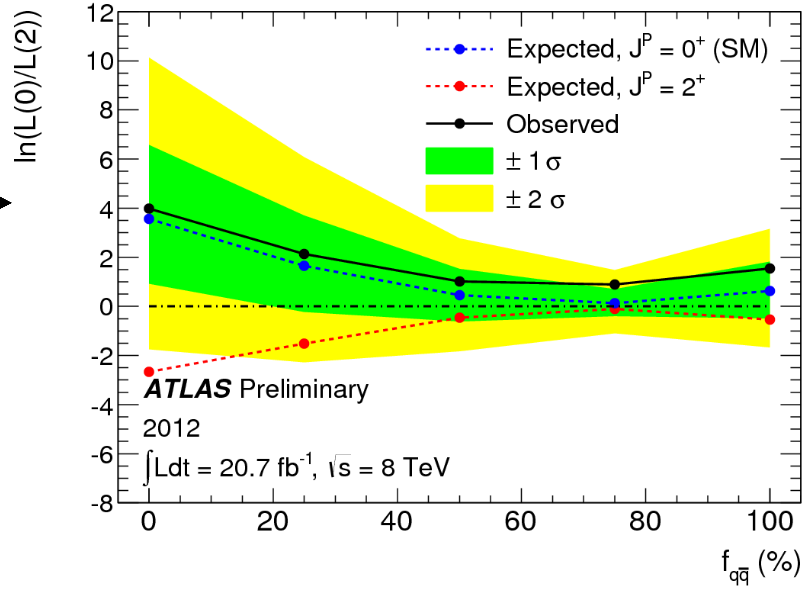
$P_{2+m}^{exp} = 0.5\%$, $p_{2+m}^{obs} = 0.3\%$, $p_{SM}^{obs} = 58.8\%$

$\Rightarrow$ $CL_s(0^-) = 0.7\%$ (10.6% for alternative analysis…)

Scan of the qq annihilation fraction in the initial state

(sensitivity degraded at high f_{qq} since SM and 2^+_m shapes more similar

$\Rightarrow$ complementarity with WW channel)

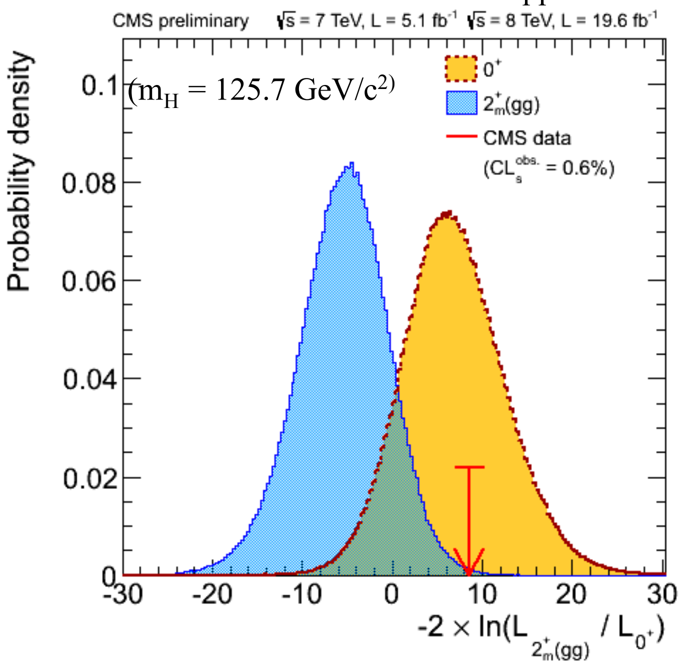


$\Rightarrow$ Data in better agreement with SM hypothesis than 2^+_m whatever f_{qq}

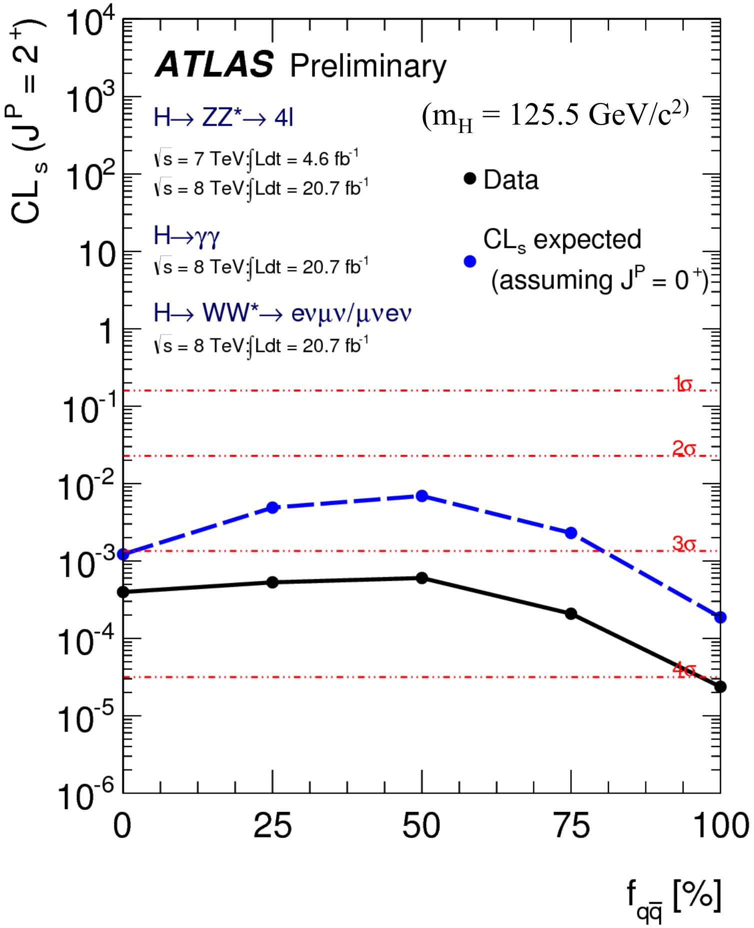
Combination

Atlas and CMS combined the WW and ZZ channels (and γγ for Atlas) to improve the sensitivity for the SM vs 2^+_m separation

CMS separation, for $f_{qq} = 0$



Atlas, as a function of f_{qq}



	ZZ	WW	Combined
p_0^{obs} (%)	81.6	33.0	63.3
p_2^{obs} (%)	0.245	9.3	0.2256
CL_s (%)	1.4	14.0	0.6

⇒ 2^+_m(gg) disfavoured with CL = 99.4% CL

⇒ Compared to SM, 2^+_m disfavoured at more than 99.9% CL whatever f_{qq}

Conclusion

- The SM hypothesis is favoured against all tested alternative models

- People willing to continue on spin measurements should take some time to define relevant (spin 2) models not already excluded by coupling measurement…

- The fermionic channels will also bring information, e.g. in the VX associated production, with $X \rightarrow b\bar{b}$, the mass of the VX system might be a very good discriminator for SM vs 0^-, 2 hypotheses

- The delicate issue of the p_T spectrum should be clarify

- For the futur, CP asymmetries seem more important to look at e.g. in the di-photon channel, the VBF production seems promising

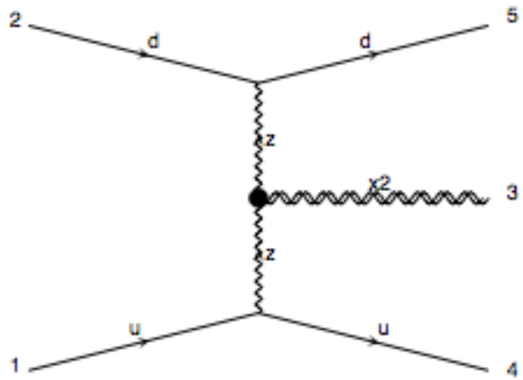
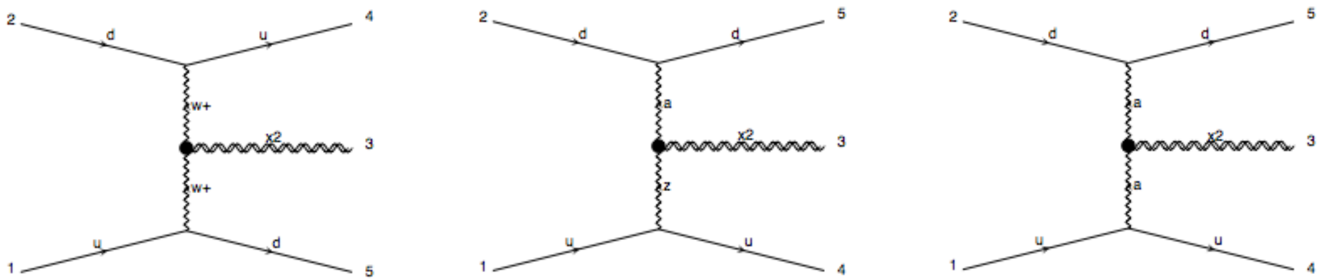


Diagram very similar to the golden channel $H \rightarrow ZZ^* \rightarrow 4l$
$\Rightarrow$ look for angular correlations in the di-jet system

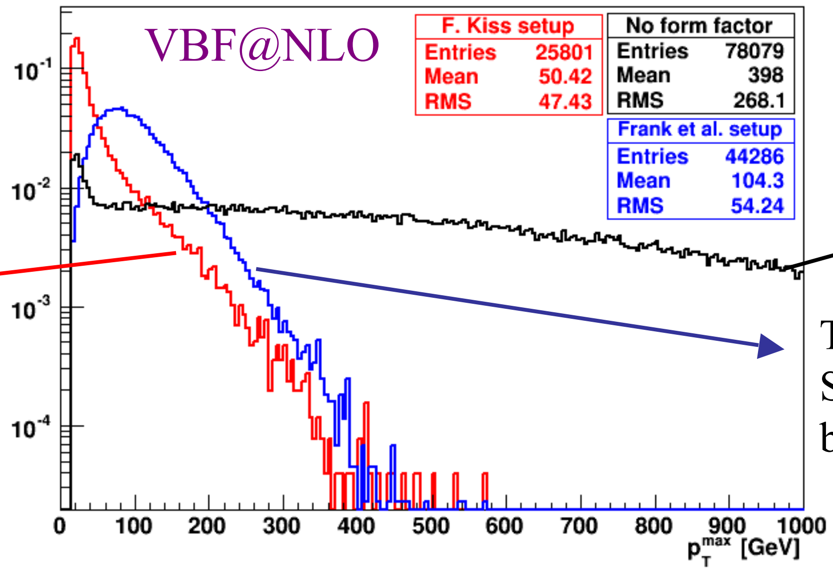
Another side remark on p_T but for outgoing partons in VBF processes :

- No “good” spin 2 model : using an effective lagrangian
  ⇒ violation of unitarity above a certain scale.
  Need form factors (FF) to regularize the cross-sections…

- Choices of couplings also relevant from the really beginning :
  the couplings X-Z^0-γ and X-γ-γ exist and can spoil the typical VBF signature
  (relatively high p_T (~ $m_V/2$) forward jets)



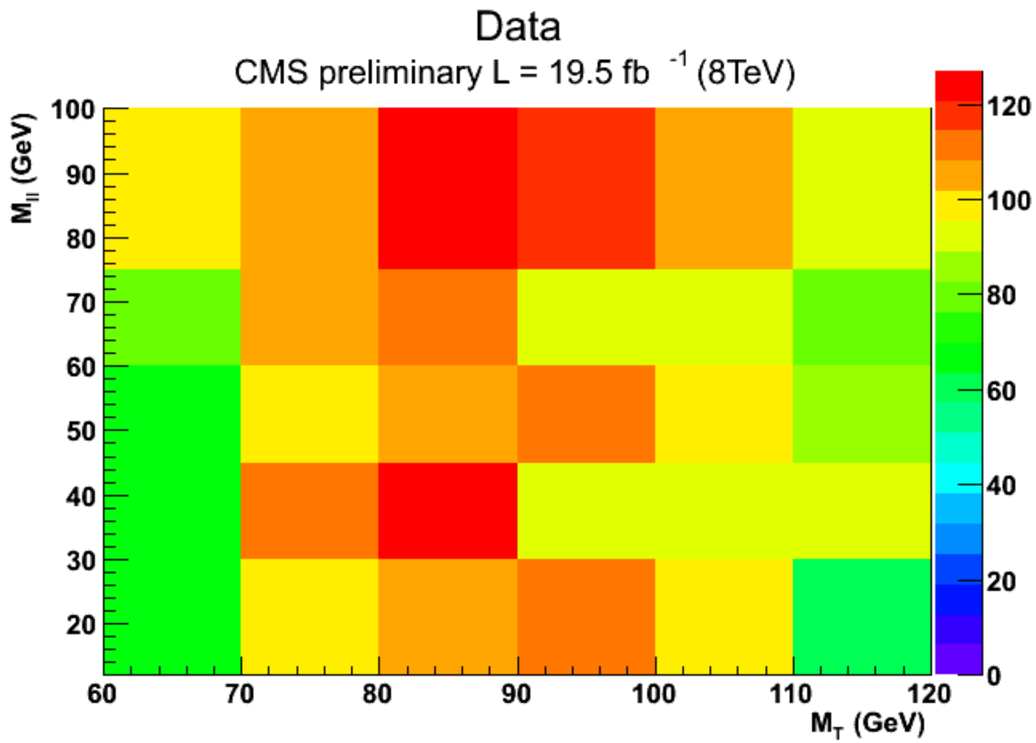
Strong contribution
from photon exchange :
⇒ low p_T jets



No FF :
Unphysical p_T
spectrum

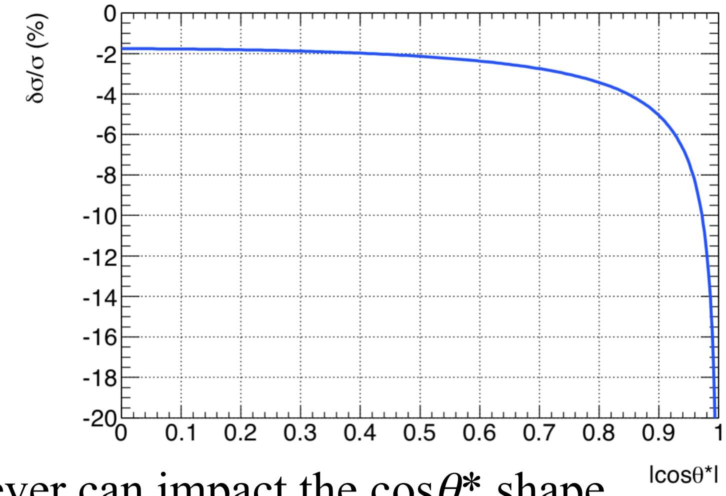
Trying to get closer to
SM Higgs boson VBF spectra
by decreasing photon contribution

CMS WW data, 0-jet bin



✓ Signal :

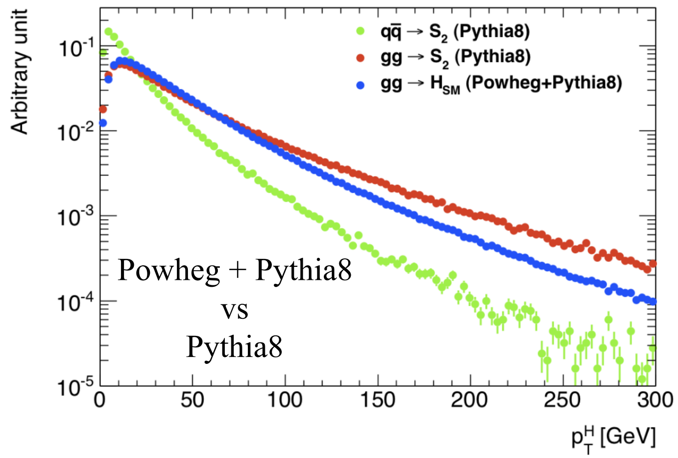
→ The interference between the processes gg → X → γγ and gg → γγ (box) depends on cosθ* and distort the shape

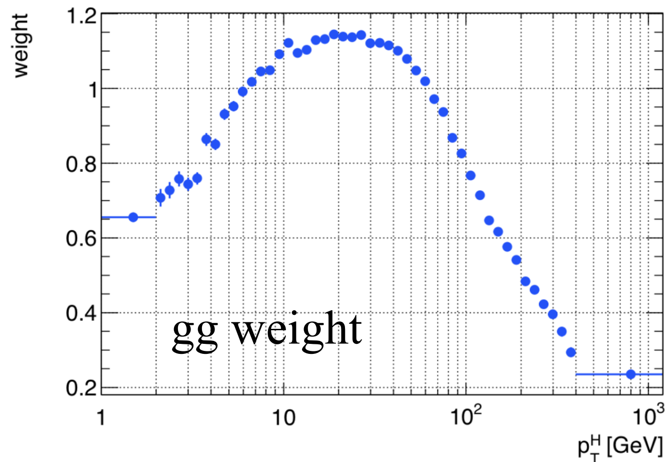


Only done for the SM : reduction of signal yield.
large at high cosθ* : correct and use the full correction as the uncertainty.

(the computation for the spin 2 model used here is available since last week (effect with opposite sign and smaller))

→ No computation of the p_T spectrum for spin 2. However can impact the cosθ* shape, especially at high cosθ* (only populated thanks to non zero p_T)
As "reasonable" guess, assume it is the same as the SM Higgs boson (for gg fusion)
⇒ reweigh spin 2 MC (gg fusion) to SM Powheg ggH p_T
use full correction as systematics (why ?? HSG7 strange prescription…)





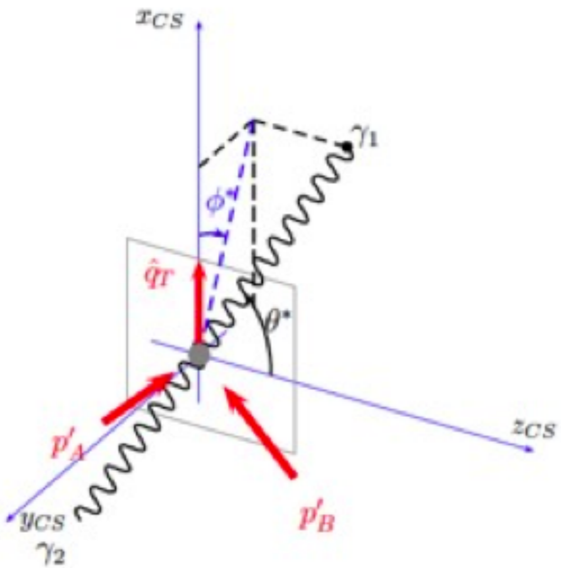
Do nothing for qq initiated process, e.g. the model for p_T is defined by Pythia8

Remark : assuming a scalar particle, the parity is very difficult to determine from the $H \to \gamma\gamma$ decay

→ Correlation in the linear polarisation of the two photons : obviously not in Atlas ($\pi^0 \to \gamma\gamma$ was used to measure the neutral pion parity)

→ From the $p_{T,H}$ spectrum distortion of 0^- vs 0^+ (due to the gluon polarisation inside the proton, hep-ph/1304.2654)

The Collins-Soper cosθ* definition :



$$\cos\theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + \left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \cdot \frac{2 p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$

$= \sinh(\Delta\eta) / (\cosh(\Delta\eta) + 1)$ at $p_{T,H} = 0$

- expected to minimise the impact of ISR
- shown to give the best discrimination (?)

The nominal (default) analysis :

(to be given up ?)

Main hypothesis : decorrelation between $m_{\gamma\gamma}$ and $\cos\theta^*$

$$\mathrm{pdf}(m_{\gamma\gamma},\cos\theta^*) = \mathrm{pdf}(m_{\gamma\gamma}) \times \mathrm{pdf}(\cos\theta^*)$$

In principle, true for the signal (up to small resolution effects due to different photon kinematic in different $\cos\theta^*$ bins)

- In the SR, 2D fit to $\mathrm{pdf}(m_{\gamma\gamma},\cos\theta^*)$
  the bkg $\cos\theta^*$ pdf is extracted from side band (SB)

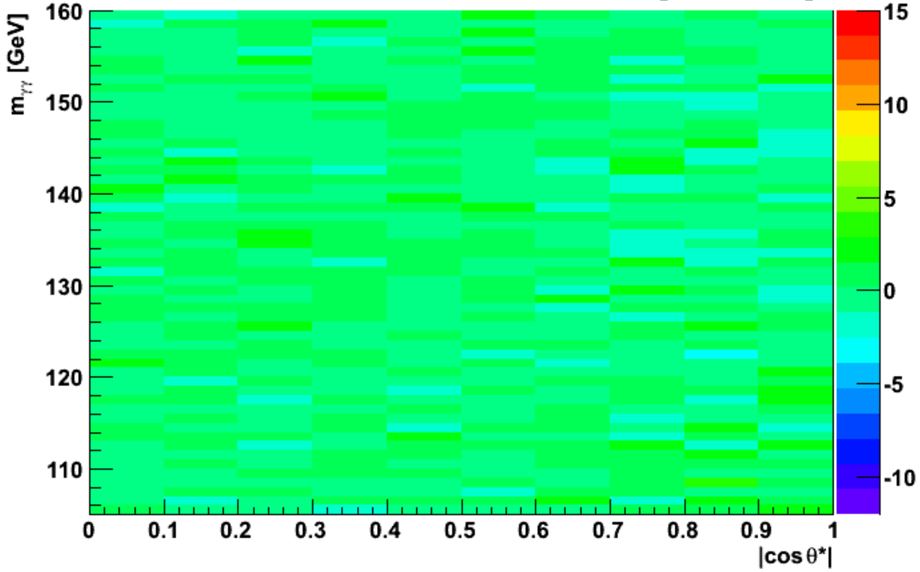
- In the SB, 1D fit to $\mathrm{pdf}(m_{\gamma\gamma})$, which is identical to the SR mass pdf
  $\Rightarrow$ constrain N_{bkg} in the SR

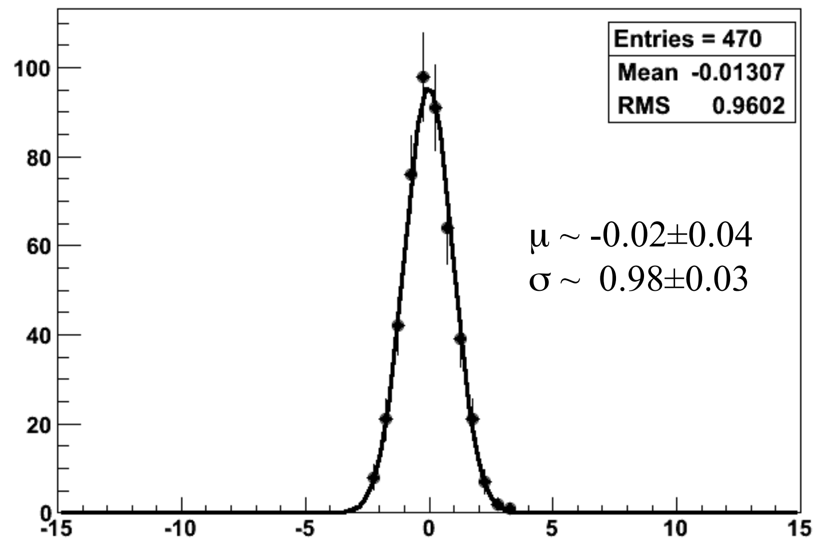
The decorrelation is checked on the data and high stat MC sample by comparing the expected number of events in a $(m_{\gamma\gamma},\cos\theta^*)$ bin assuming decorrelation to the observed one :

$$n^{exp}[m_{\gamma\gamma}][\cos\theta^*] = \frac{\overbrace{\sum_{m'_{\gamma\gamma}} n^{obs}[m'_{\gamma\gamma}][\cos\theta^*]}^{=n^{obs}[\cos\theta^*]} \cdot \overbrace{\sum_{\cos\theta^{*\prime}} n^{obs}[m_{\gamma\gamma}][\cos\theta^{*\prime}]}^{=n^{obs}[m_{\gamma\gamma}]}}{n^{tot}}$$

$$\left(\sigma^{exp}[m_{\gamma\gamma}][\cos\theta^*]\right)^2 = n^{exp}[m_{\gamma\gamma}][\cos\theta^*] + \left(n^{exp}[m_{\gamma\gamma}][\cos\theta^*]\right)^2 \cdot \left(\frac{1}{n^{obs}[m_{\gamma\gamma}]} + \frac{1}{n^{obs}[\cos\theta^*]} + \frac{1}{n^{tot}}\right)$$

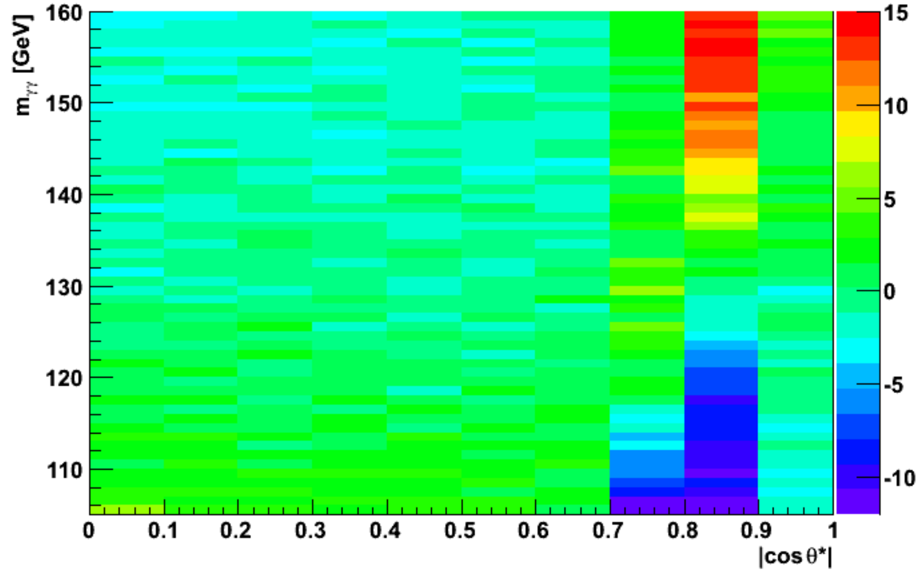
And use the pull : $(n_{obs} - n_{exp}) / \sigma_{nexp}$

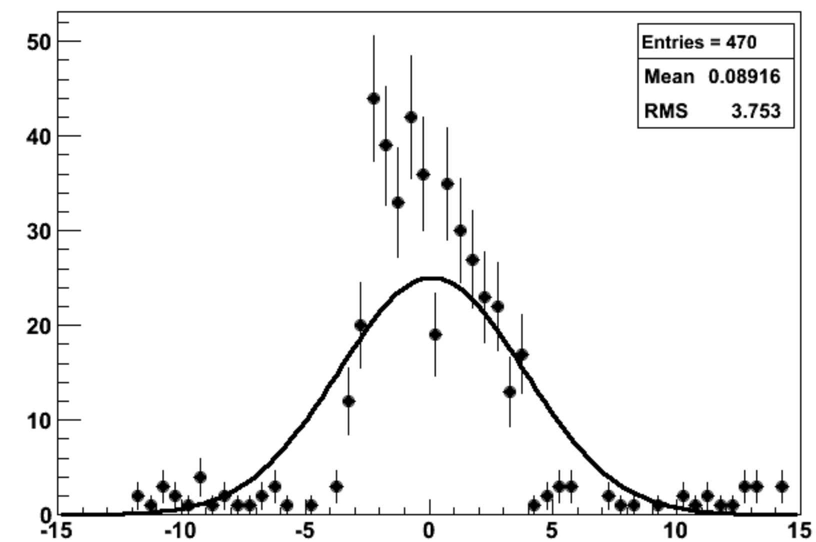




With absolute p_T cuts (used for HCP analysis) a strong correlation is observed :

this would require a true 2D bkg pdf (very intricate…) or the use of an "averaged" 1D cosθ* pdf (choice for HCP)





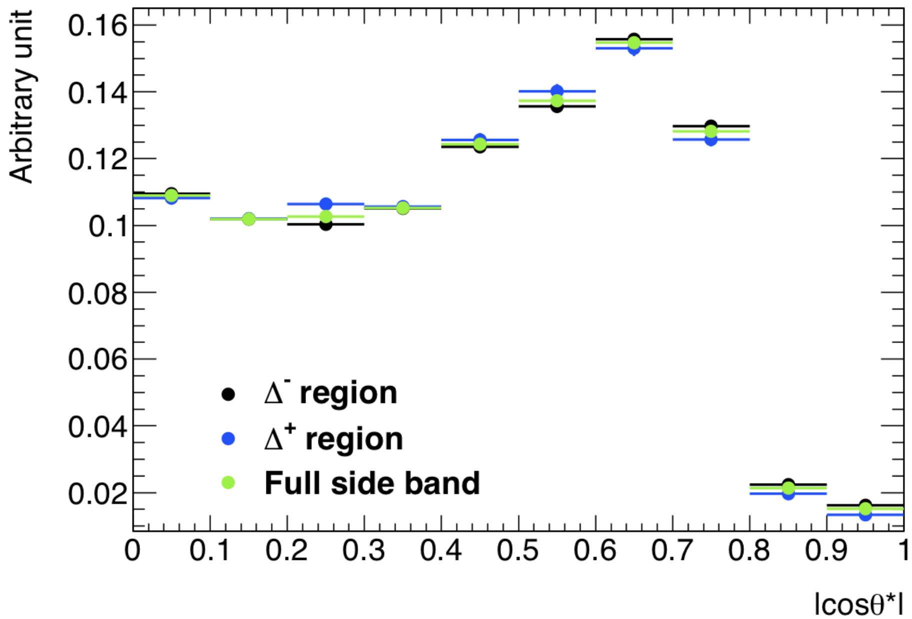
The mass pdfs (analytical functions) :

- ✓ bkg : a five order polynomial (5 + 1 nuisance parameters (NP)) + spurious signal (1 NP)

- ✓ signal : a standard Crystal-Ball + Gaussian parameterisation used for all cosθ*
  (including ESS and resolution systematic uncertainties : 6+1 NP)

The cosθ* pdfs (10 bin histograms) :

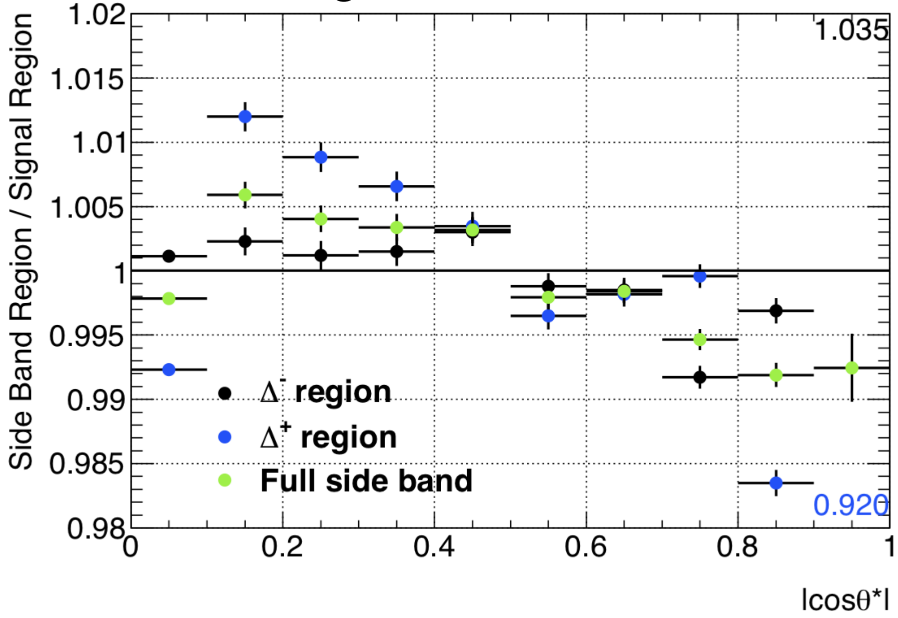
- ✓ bkg : from the full SB ($m_{\gamma\gamma} \in [105,122[\cup]130,160]$ GeV/c^2)



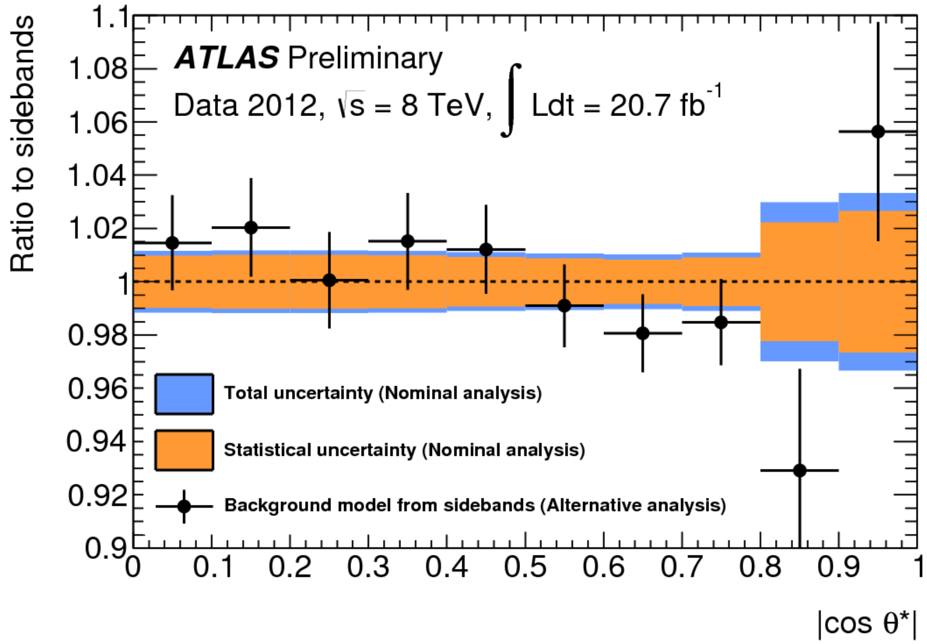
Each bin is assigned a nuisance parameter with a Gaussian constrain (10 NP) :

- for the finite statistics in the SB
- to account for the remaining correlation observed in the high stat. MC

High stat. MC SB / SR



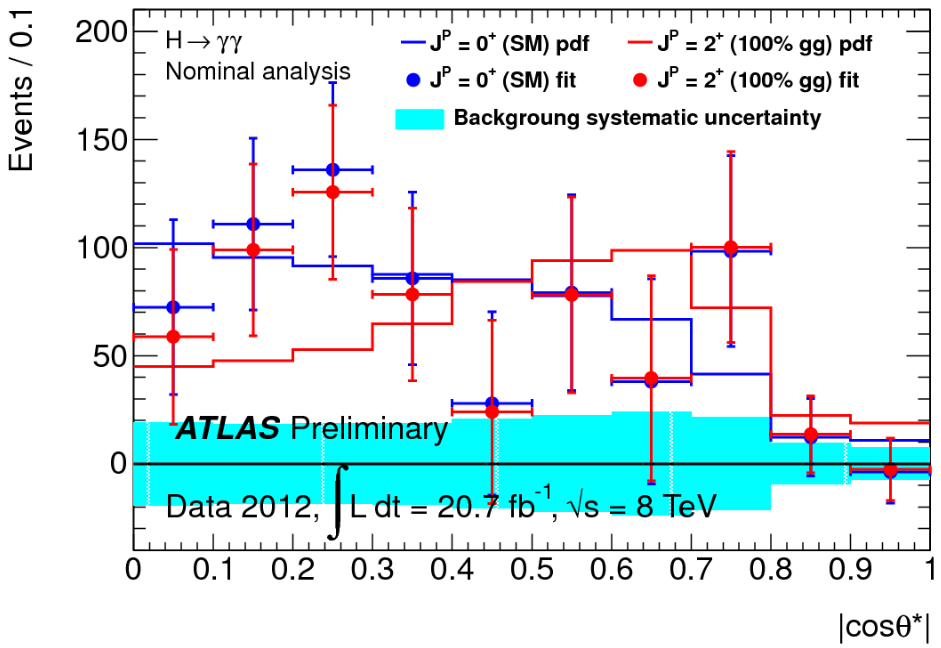
Final systematics per bin



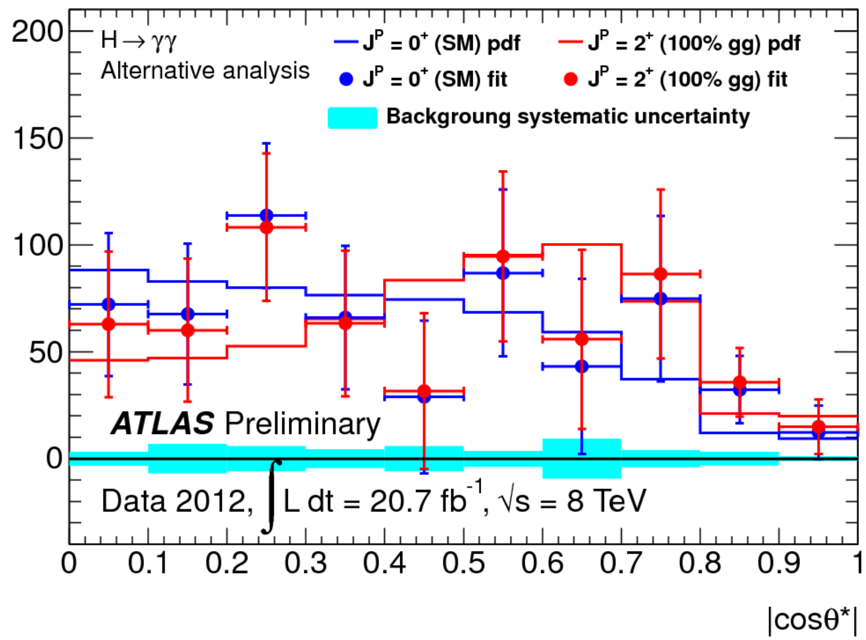
From ~ 1 to ~ 4% systematic uncertainty depending on $\cos\theta^*$

Fitted bkg subtracted data

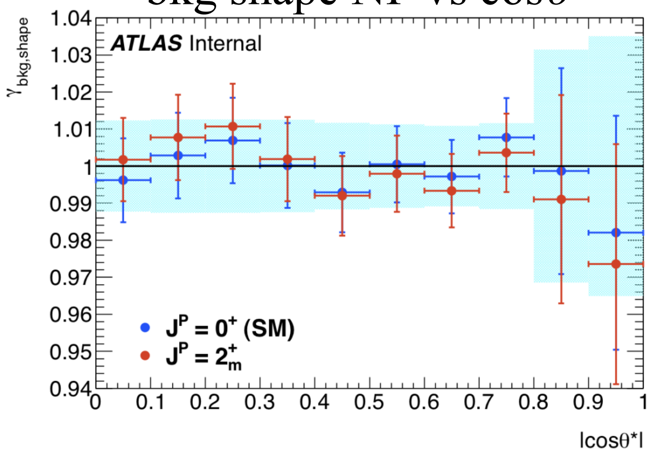
Nominal analysis



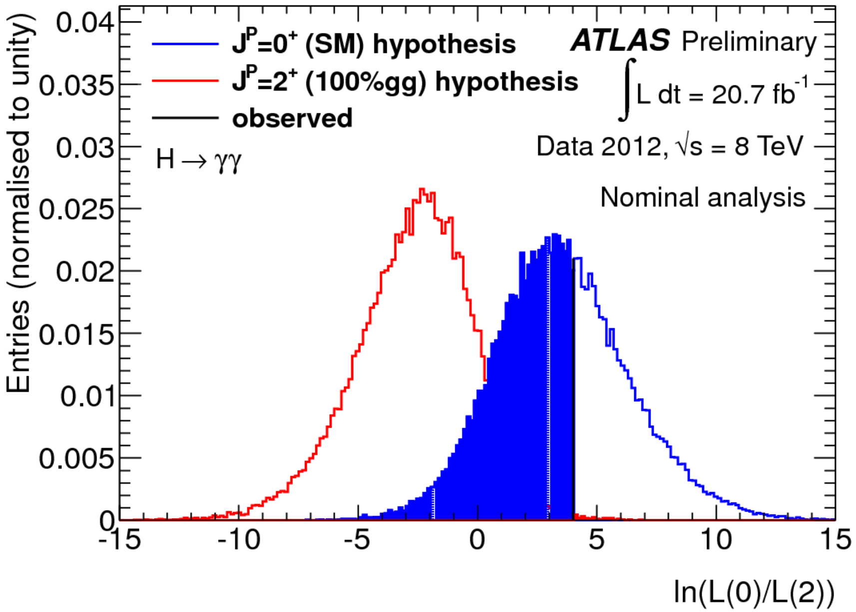
Category analysis



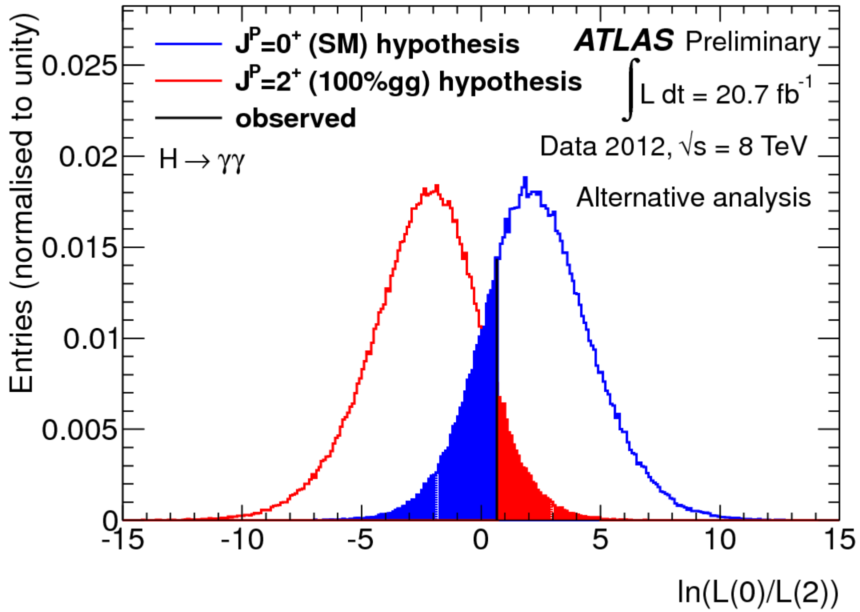
bkg shape NP vs cosθ*



Nominal analysis



Category analysis



Analysis	Hypothesis	N_S	p-values (%) expected	p-values (%) observed	$CL_S(2^+)$ (%)
Nominal	SM	690±150	1.2	58.8	0.7
	2^+	620±160	0.5	0.3	
Categories	SM	570±120	1.9	21.1	10.6
	2^+	590±130	1.7	8.4	

Enforcing decorrelation in the Category analysis gives results similar to the nominal analysis

The category (alternative) analysis :

Do a simultaneous fit to the data invariant mass distributions in 10 cosθ* bins : 10 categories

The mass pdfs (analytical functions) :

✓ bkg : 1 shape / cosθ* bin (9 exponentials of degree 2 polynomial + 1 degree 3 polynome)
21 (shape) + 10 (normalisation) + 10 (spurious signal, constrained) = 41 NP

✓ signal : can cope with the slighly varying resolution as a function of cosθ*
by using 10 different CB + Gaussian shapes (7 standard ESS and resolution NP)

The cosθ* information :

✓ signal : use the predicted relative yield / cosθ* bin
same systematics as for the inclusive analysis, treated as bin to bin migrations

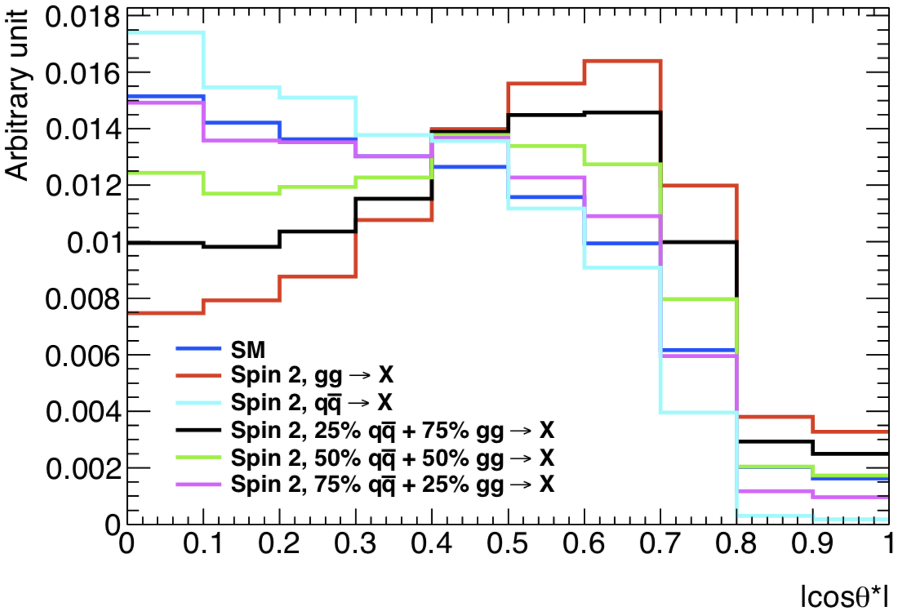
✓ bkg : the shape is an outcome of the fit

Main drawbacks :
many NP for the bkg mass shapes, needs spurious signal studies

Main advantage :
can deal with signal mass shape varying as a function of cosθ*
no bkg cosθ* pdf, no decorrelation assumption needed

The decorrelation can be enforced by using the same bkg mass shape (same parameters) in all bins (still keeping a spurious signal NP / bin ?)

As a function of $q\bar{q}$ annihilation fraction (f_{qq})



Pdf as a function of the fraction of f_{qq}

(fraction in the selected sample, corresponding to a slightly lower fraction at the production level due to a higher efficiency in the $q\bar{q}$ annihilation process)

Smaller discrimination at high f_{qq}
minimal separation @ $f_{qq} \sim 25\%$